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THE MINERALOGICAL MAGAZINE

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Vol. XXII.

*A study of the calc-gneisses, scapolite-gneisses, and
cordierite-garnet-sillimanite-rocks of Coimbatore,
Madras Presidency; with comparison to
other similar occurrences in India.¹*

(With Plate V.)

By L. A. NARAYANA IYER, M.A., Ph.D., D.I.C., F.G.S.
Geological Survey of India.

[Communicated by Professor W. W. Watts, F.R.S.; read March 19, 1929.]

I. Introduction.

THE Indian peninsula, though considered to be a very stable part of the earth's crust and hence called the 'Indian Shield', shows in different parts evidence of formerly having sustained epicontinental basins, in which sedimentation occurred. These sediments are now found in detached prisms as crystalline gneisses and schists in different parts of India, e. g. in the Madras Presidency, Bihar and Orissa, Central Provinces, Central India, and Rajputana. They have been found overlying the ancient gneisses (Archaean), and belong to a division known in Indian geology as the Dharwar System.

The material to be described was collected in the Coimbatore district by the author in 1915, while a student of the Madras University. A short preliminary paper was read at the Geological Section of the Indian Science Congress held at Nagpur in 1920, and the work has since been completed by him as a research student in the Imperial College of Science and Technology, London.

¹ Published by permission of the Director, Geological Survey of India.

There are no published reports on the occurrence of these rocks in this part of the Madras Presidency, though Mr. C. S. Middlemiss made incidental mention of the calc-gneisses in his Presidential Address, 'Complexities of Archaean geology in India',¹ to the Geology Section of the Indian Science Congress at Bangalore, and also in 'The geology of the Idar State'.² But similar rocks collected over a century ago in the neighbouring district of Salem have been studied by A. Lacroix,³ and the portion of his paper bearing on South India was translated by F. R. Mallet.⁴ Lacroix's paper gives no definite information about the locality, so that it is not possible to ascertain the relation of the rocks he describes. He mentions the occurrence of biotite- and sillimanite-gneisses, and states that identical rocks occur in Salem and Ceylon.

II. *Geology of the area.*

The rocks forming the subject of this paper outcrop in low hills which rise towards the west. They can be divided into two distinct groups: (1) the cordierite-garnet-sillimanite-rocks (schistose, and in some places gneissose), and (2) the scapolite-gneisses with associated marble beds and calc-gneisses. The rocks of the plains consist mainly of biotite- and feldspathic gneisses, which are not considered in this paper.

The rocks of the first group were at first called 'garnet-sillimanite-schists', but they are now described as cordierite-garnet-sillimanite-rocks, since cordierite has been found in them. They occur close to the railway station near Madukarai, a few hundred yards along the road to Coimbatore, and to the west they form the main mass of the Dharmalingham malai [hills]. They were traced as far as the Walayar river. The hills trend in a general ENE.-WSW. direction, and the foliation of the gneisses strikes NNE.-SSW.

The scapolite-gneiss is found overlying the last-named rocks on their northern and southern sides, forming two arms extending on either side of the Dharmalingham hills. The northern arm was traced only to a distance of 3-4 miles. The southern arm, occurring as detached outcrops in the form of small hills, was traced for a distance of 10-12 miles. Scapolite-gneiss also forms small hills in a

¹ C. S. Middlemiss, Journ. Asiatic Soc. Bengal, 1917, n. ser., vol. 13, pp. cxv-cxii.

² C. S. Middlemiss, Mem. Geol. Survey India, 1921, vol. 44, pp. 42-43.

³ A. Lacroix, Bull. Soc. Franç. Min., 1889, vol. 12, p. 282.

⁴ A. Lacroix, Rec. Geol. Survey India, 1891, vol. 24, p. 155.

roughly elliptical area on the eastern side of the road from Madukarai to Coimbatore. Calc-gneisses are interbanded with the scapolite-gneiss.

The marble forms the base of the hills, weathering with smooth surfaces. It forms a marginal fringe of the eastern elliptical area of scapolite-gneiss, with a short extension to the west; and on the south

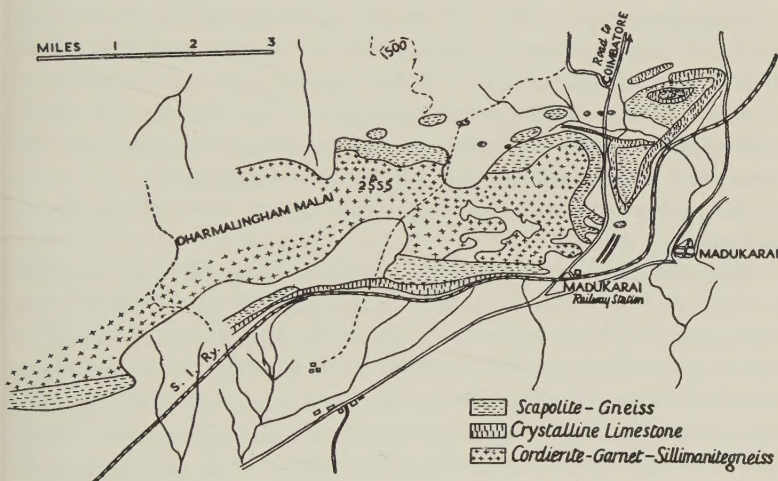


FIG. 1. Geological map of South Coimbatore taluk, Madras Presidency.

side of the Dharmalingham hills it extends for some distance along the railway line.

Pegmatite veins and lenses of quartz penetrate the cordierite-garnet-sillimanite-rocks and the crystalline limestone.

III. *The cordierite-garnet-sillimanite-rocks.*

General characters.—The texture and structure of these rocks vary in different localities. Sometimes they are more schistose, and at others they have a very coarse texture, with 'tabloid' aggregates composed of colourless minerals, such as sillimanite and quartz, occasionally associated with a little garnet, cordierite, and biotite. The 'tabloids' measure 2 to 3 in. in length, and are arranged along the direction of foliation, standing vertically, as seen near the railway station and near Karaipathy, $1\frac{1}{2}$ miles WNW. of the same locality. As these are composed of hard minerals, not easily disintegrated,

they are found lying loose on the ground as the result of weathering. Sometimes the rocks are so fine grained that the 'tabloids' become very minute and are visible only under the microscope; they show no divisional planes.

Mineral composition.—The chief mineral components are quartz, biotite, sillimanite, garnet, cordierite, iron-ore, a little felspar, and some flakes of graphite. The cordierite present could not be detected in hand-specimens. The sillimanite and the biotite flow round and fold over the garnets, giving rise to 'augen' structure. The rock is sometimes greyish in colour (perhaps due to the grains of cordierite), or reddish-brown, exposing a large number of small, reddish, round garnets which weather out and strew the ground. The amount of biotite present varies in different localities.

The following rock types are represented by the specimens collected:

Specimen no. 2, from the line of hills a little NW. of Madukarai railway station. This is a very coarse grained garnetiferous sillimanite-schist and shows a very definite banding in the direction of the strike of the gneiss (NNE.-SSW.). It is brownish-red in colour, due to the coppery colour of the biotite. The 'tabloids', or platy aggregates of minerals, occur in abundance, standing out prominently on the surface of the rock. There are plenty of garnets among the sillimanite bundles, giving the 'augen' structure. The ground-fabric of these plates consists of quartz, biotite, garnet, iron-ore, and graphite.

Specimen no. 10 is one of the 'tabloids' picked from the weathered surface of the hill near Madukarai. Sillimanite needles are visible to the unaided eye; the garnets form the brown spots, round which curve the sillimanite bundles or needles. Biotite is present to a very small extent. Under the microscope the rock is seen to consist of bundles of sillimanite both as thick and needle-like crystals, and also as sheaf-like aggregates flowing round the pinkish garnet (pl. V, fig. 1).

Specimen no. 16 is a cordierite-garnet-biotite-sillimanite-gneiss from near Madukarai. This is also a greyish rock, rather fine grained and showing a definite foliation. The garnets are very minute and scattered. The structure of the rock is rather gneissose. Under the microscope it is a granoblastic, medium grained, banded rock made up mostly of colourless cordierite, quartz, and biotite. There is a little felspar, both orthoclase and albite being present. The biotite occurs as irregular brownish grains and at times as

rectangular plates, oriented parallel to the direction of pressure. The garnet is pink, irregular elongated eye-shaped, and contains inclusions of quartz. The sillimanite occurs as hairy bunches or sheaves, as slender needle-shaped crystals, and as small needles in quartz.

Specimen no. 9 (pl. V, figs. 2 and 3) is another of the same rock, but more coarse grained than the above. It also shows regular banding, the biotites being arranged with their longer axes parallel to the foliation direction. There are also rounded and elongated eyes of garnet with bundles and fibres of sillimanite flowing round them. The garnets show also longitudinal cracks at right angles to the direction of foliation. A little albite showing characteristic twinning is also present, with an extinction-angle of $5-6^{\circ}$. Cordierite makes up the larger part of the rock, occurring as large plates having poikilitic inclusions of quartz. It shows a fine striation, its refractive index is lower than that of quartz or Canada-balsam, and it shows a very faint pleochroism.

The cordierite in these rocks is perfectly fresh and does not show any alteration to pinité, nor does it show pleochroic haloes or lamellar and sector polarization, which are usually present in this mineral. Further, it is optically positive, like the cordierite found by Mr. I. C. Chacko in Travancore in a dioritic rock¹; and also described by Dr. M. S. Krishnan² from the Madura district of the Madras Presidency, where it is formed as a result of the contact metamorphism of an Archaean biotite-gneiss by an intrusive tongue of charnockite. The association of minerals also seems to be identical in this occurrence, since cordierite in varying proportions occurs with pinkish garnets, sillimanite, magnetite, titanoferrite, orthoclase, and oligoclase.

IV. *The scapolite-gneiss.*

Weathering, joints, and folding.—The action of the weather seems to have had a greater effect on the scapolite-gneiss. It is found grooved along the foliation direction. Abundant garnets stand out on the surface, and they are arranged in the direction of foliation. The scapolite-gneiss shows a very marked jointing, appearing rather slaty at a distance, owing to the grooved nature of the surface and the joint-planes. There is no cleavage as in slates, and joints are due to

¹ I. C. Chacko, *Geol. Mag.*, 1916, dec. 6, vol. 3, p. 462.

² M. S. Krishnan, *Min. Mag.*, 1924, vol. 20, p. 248.

tension during the folding. The joints have also been affected by the folding, for they show anticlinal and synclinal structures. Such complex folding can be seen in the detached blocks as well as on the hills themselves. Near the sixth milestone from Coimbatore to Madukarai huge well-jointed blocks of the rock are seen in large numbers (fig. 2). Numerous kinds of complex folding are visible in the detached blocks, but the main direction of the joint-planes runs along the foliation direction. The rock also breaks in thick slabs, sometimes flat, or sometimes curved if the joint-planes show folding. In this locality garnets are so abundant that they strew the ground at the base of the hills. They are generally small, but in the NE. corner of the hill they are of large size, about 2-3 in. in diameter.

The scapolite-gneiss does not vary in appearance. It is a greyish rock, very compact, and medium to fine grained. The ferromagnesian minerals appear as small spots, following the gneissic structure. The weathered surface effervesces slightly with acid owing to the presence of calcite.

Rock types.—A specimen from Madukarai is grey and white in colour and granoblastic with medium to fine grain. The chief minerals are a bright-green augite, plagioclase feldspar, quartz, scapolite, calcite, sphene, and iron-ore. Under the microscope (pl. V, fig. 4) it is even grained and granulitic, showing banding. The colourless minerals are scapolite, calcite, and quartz, which form the greater part of the rock. The scapolite occurs as large, rectangular or square idioblastic plates, showing the characteristic cleavage, refractive index, birefringence, and straight extinction. Basal sections show two sets of cleavage and a good uniaxial figure. It is also present as inclusions in pyroxene, and at times is surrounded by the feldspars. The scapolite itself has some inclusions of quartz. Quartz occurs interstitially as large elongated grains and has longitudinal cracks, showing that it was subjected to lateral pressure. Calcite is less common and occurs interstitially between the pyroxenes and scapolite, or often surrounding the latter. The feldspar is mostly albite or oligoclase, and its long twin-lamellae have an extinction-angle of $10-14^{\circ}$. It occurs interstitially and sometimes enclosing the scapolite crystals. One large idioblastic crystal of feldspar is seen enclosing scapolite. A few grains of apatite are also present. Among the ferromagnesian minerals, a green diopside, often paramorphosing into hornblende, is very common. The hornblende shows the characteristic basal sections, pleochroism from green to brown, and an

extinction-angle of 15° . Sphene occurs as irregular and idioblastic grains. A few grains of garnet and a little biotite and magnetite are also present. Crystalloblastic order: magnetite, sphene, apatite, part of scapolite, pyroxenes, scapolite, feldspar, and quartz.

Another interesting micro-section (pl. V, fig. 5) of these rocks is mostly made up of quartz, feldspars (oligoclase and albite), pyroxenes,

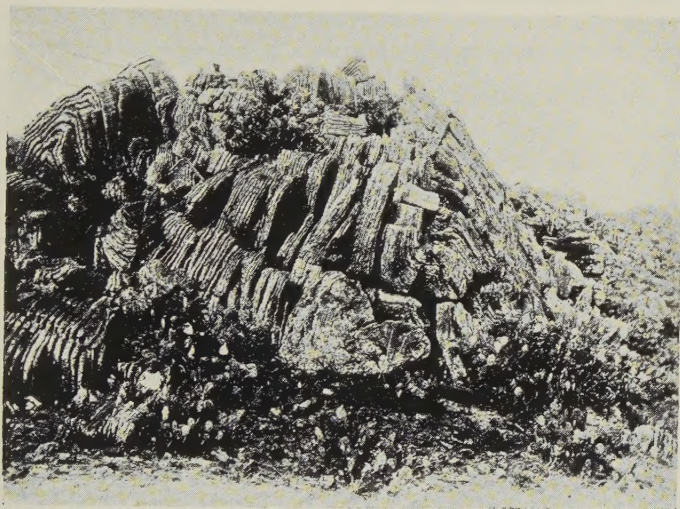


FIG. 2. Folding in scapolite-gneiss, near Madukarai, Coimbatore.

[From 'Geography of the Madras Presidency', by E. Thurston.

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and a little calcite. The feldspar is both twinned and untwinned, and is more abundant than in the previous rock, occurring as elongated plates. This rock is entirely free from scapolite. The pyroxene contains veins of calcite and quartz, perhaps produced during the alteration of pyroxene to hornblende. Feldspars consist of both oligoclase and albite, which have extinction-angles of $5-10^{\circ}$. The pyroxene is dark green in colour, with less strongly coloured margins and interiors. It also contains inclusions of quartz and feldspars. Crystalloblastic order: apatite, sphene, part of quartz and feldspar, pyroxenes, feldspars, and quartz.

This rock is really the result of recrystallization due to metamorphism in which the scapolite has been altered into feldspars and pyroxenes. Evidence for this is given by the presence of quartz-

felspar intergrowings ('quartz de corrosion' or myrmekite) on the margins of most of the felspar crystals. A similar phenomenon, with felspars forming a considerable part of the rock when no scapolite is present, has also been recorded by Adams and Barlow.¹ In the calc-gneisses of the Central Provinces in India, R. C. Burton² connects the refusal of similar rocks during metamorphism with the presence of vermicular inclusions of quartz.

V. *The crystalline limestone and calc-gneiss.*

The limestone grades from coarsely crystalline to fine in texture, and in colour through grey, pink, and white. Under the microscope (pl. V, fig. 6) the rock is medium to coarse grained, mostly made up of crystalline calcite having irregular edges. Twin-lamellae are not always developed. Some of the limestones are free from the lime silicate minerals, but in others their gradual development could be traced; the rock then grading into a calc-gneiss and often interbanded with the scapolite-gneiss. The pyroxenes begin to grow as small round grains in the calcite and gradually attain a larger size. Hornblende is also formed at times directly from the limestone, and so also a little biotite. Besides the above, small amounts of apatite, magnetite, sphene, and ilmenite altering to leucoxene are also present. The effect of pressure is evident, for the quartz shows undulose extinction, and the twin-lamellae in the calcite are sometimes bent and twisted.

VI. *Occurrence of similar rocks in other parts of India.*

Madras Presidency.—The occurrence of similar rocks in the Salem district has already been referred to. The next occurrence of these rocks is in the Ganjam and Vizagapatam districts, recorded by Dr. T. L. Walker.³ Here the rocks consist of quartz, garnet, sillimanite, and graphite, and they form well-defined schists. He considers them as apparently altered sediments, overlying the granitoid gneiss, charnockite, and more massive gneisses of the crystalline complex. He has also recorded the occurrence of garnetiferous quartzite and calc-gneisses, interbanded with the sillimanite-rocks. The association of the sillimanite-schist with these rocks is thought to

¹ F. D. Adams and A. E. Barlow, *Geology of Bancroft and Halliburton areas, Province of Ontario*. Geol. Survey Canada, 1910, Mem. no. 6, pp. 102–113.

² R. C. Burton, *Rec. Geol. Survey India*, 1915, vol. 45, p. 102.

³ T. L. Walker, *Mem. Geol. Survey India*, 1901, vol. 33, p. 8.

be an additional reason for regarding them as para-schists; while their occurrence above massive igneous rocks (charnockites, &c.) suggests that they are rocks formed by the metamorphism of ancient sediments.

The late Mr. E. W. Vredenburg¹ has mentioned that the khondalite and the Bezwada gneiss are identical, and describes them as consisting of quartz, sillimanite, and graphite; but W. B. King and R. B. Foote² do not mention the presence of sillimanite in the Bezwada gneiss, which they define as a quartzo-felspathic micaceous schist. Dr. King called it a murchisonite-gneiss. The abundance of murchisonite and the absence of sillimanite make it doubtful whether the Bezwada gneiss and the khondalites are identical.

In connexion with the manganese ores at Kodur, Dr. L. L. Fermor³ mentions the occurrence of khondalites. Here also the calc-rocks are found next to khondalites.

Central Provinces.—Another occurrence of the garnet-sillimanite-rocks has also been recorded by Dr. Fermor in the Sausar tahsil.⁴ He describes the gneisses in this area as ortho-gneisses, consisting of feldspars (microcline, orthoclase, oligoclase, and labradorite), garnets in some places, and occasionally sillimanite. These are considered to have resulted from pressure on the original gneiss, and are not to be taken as any indication of the presence of assimilated sediments. R. C. Burton⁵ has considered some of the gneisses to be crush conglomerates, in which flat, ellipsoidal, and tabloid bodies have been developed in biotite-granite and gneisses as the result of crushing.

With regard to certain of these garnet-sillimanite-gneisses or schists, and the finer grained biotite-gneisses, W. D. West⁶ suggested that the rocks of these two horizons may be metamorphosed sediments. Later, in 1926, when the field relations of some of these gneisses had become better understood, he stated that the variety of muscovite-biotite-gneiss, which contains small tabloids rich in sillimanite, occurs always at the base of the dolomite suite and nowhere else, and that chemical analysis has proved it to be a para-gneiss.⁷

¹ E. W. Vredenburg, *A summary of the geology of India*, 2nd edit., 1910, p. 14.

² W. B. King and R. B. Foote, *Mem. Geol. Survey India*, 1879, vol. 16, pp. 12-14.

³ L. L. Fermor, *Ibid.*, 1909, vol. 37, p. 1046.

⁴ L. L. Fermor, *Rec. Geol. Survey India*, 1916, vol. 47, pp. 34-35.

⁵ R. C. Burton, *Ibid.*, 1915, vol. 45, p. 133.

⁶ W. D. West, *Ibid.*, 1925, vol. 59, pp. 75-81.

⁷ General Report, *Ibid.*, 1926, vol. 60, p. 97.

Calc-gneisses.—*Madras Presidency.*—Calc-gneisses have been described by Dr. Walker in the Ganjam and Vizagapatam districts in connexion with the khondalites. The frequent association of the charnockite series with scapolite- and calc-gneisses is also mentioned by Sir T. H. Holland,¹ but he says that for want of field evidence bearing on the relation of these rocks to the charnockite series it is not possible to decide the origin of the accessory minerals. Dr. Fermor has also described them in connexion with the manganese ores of the Vizagapatam district. At Chintelavalsa in the same district the rock is a wollastonite-gneiss, and at another a scapolite-gneiss composed of scapolite and a green pyroxene with some untwinned felspar, calcite, and sphene.² Thus the calc-gneisses in all these areas show that they must have been formed by the metamorphism of impure calcareous sediments, and Dr. Fermor states that the scapolite-bearing rocks are to be considered as belonging to the series of the khondalites. The origin of the calc-gneiss and the crystalline limestone has been a subject of controversy. Professor J. W. Judd³ in 1896 advanced reasons for believing that the crystalline limestone of Upper Burma was formed chemically from pre-existing basic gneisses.

Central Provinces.—This theory was considered to hold good in the case of the Chindwara district by Dr. Fermor,⁴ who ascribed the origin of the crystalline limestone to the chemical alteration of pre-existing rocks containing an abundance of lime-felspars and magnesium silicates, the agent being carbon dioxide in solution; but further work enabled him and the late Mr. Burton to come to the conclusion that they must have been derived from a series of sediments by processes of metamorphism. This controversy has been summarized by Mr. C. S. Middlemiss in his paper 'Complexities of Archaean geology in India'.⁵

Idar State.—Mr. Middlemiss⁶ has come across similar rocks in the Idar State, and fortunately in one place, in the proximity of an intrusion of Idar granite, he has traced a crystalline limestone passing

¹ T. H. Holland, Mem. Geol. Survey India, 1900, vol. 28, p. 232.

² L. L. Fermor, Ibid., 1909, vol. 37, p. 1112.

³ C. B. Brown and J. W. Judd, Phil. Trans. Roy. Soc., 1896, vol. 187, p. 205.

⁴ L. L. Fermor, Rec. Geol. Survey India, 1915, vol. 45, p. 100, and 1906, vol. 33, pp. 166-171.

⁵ C. S. Middlemiss, Journ. Asiatic Soc. Bengal, 1917, n. ser., vol. 13, pp. cxcv-ccii.

⁶ C. S. Middlemiss, Mem. Geol. Survey India, 1921, vol. 44, p. 59.

into undoubted sedimentary rock. At other places he finds only the completely metamorphosed derivatives. In other areas in India the metamorphism has been so intense that no remnants of the original rock have been left to show a transition from the unmetamorphosed to the crystalline rock; but in Idar evidence for both is available.

Adams and Barlow¹ have traced the action of granite intrusions on limestones, and they have described rocks of similar origin, passing from a calc-silicate-scapolite-rock into a granular pyroxene-rock with some scapolite, and into pyroxene-gneisses and amphibolites.

VII. *Metamorphism in these rocks.*

From a consideration of the several occurrences in India of this suite of rocks, it becomes evident that in Coimbatore we have quite a similar suite of rocks, derived from almost similar sedimentary rocks by processes of metamorphism. Now it has been suggested that there is no reason to believe that they are ortho-gneisses derived from igneous rocks. But in the case of the calc-gneisses, the metamorphism has been observed to be due to 'lit-par-lit' intrusion of an acid magma, or the action of an intrusive granite as in the case in Idar State. The garnet-sillimanite-rocks bring in also other important types of metamorphism.

Dr. T. L. Walker (loc. cit., 1901), instead of adhering to the cumbersome name of garnet-sillimanite-gneisses or schists, has given them a simpler name, 'khondalite', since they were found in the country of the Khonds. The cordierite-garnet-sillimanite-gneiss in Coimbatore forms quite a distinct metamorphic facies, since it contains both biotite and cordierite. The khondalites must have been derived essentially from arenaceous rocks, whereas the Coimbatore rocks must have been derived from argillaceous rocks. To replace the cumbersome name 'cordierite-biotite-garnet-sillimanite-gneisses', if I may follow the example of Dr. Walker without further burdening Indian geological terminology, I would suggest that these rocks be called 'madukarite', since they were discovered near Madukarai.

With regard to the calc-gneisses of the area, they have not been mixed with the biotite-gneisses as in other areas: there is no positive evidence that they are hybrid gneisses. The only evidence of igneous intrusion in these rocks is the presence of pegmatite and quartz veins in the crystalline limestone, but these have not been met with in the

¹ F. D. Adams and A. E. Barlow, loc. cit., 1910, pp. 87, 88.

scapolite-gneiss. Moreover, crystalline limestone has been found to be intercalated with the scapolite-gneiss, the one passing into the other. The gradation implies a gradual change in the composition of the calcareous sediments, or the alternation of layers differing in composition. But it cannot be denied that the intrusion of the neighbouring masses of the charnockites and gneisses must have influenced the metamorphic processes of the area considerably.

The metamorphic processes.—The study of these rocks would be incomplete without a consideration of the metamorphic processes involved in their formation. Since the three factors of temperature, pressure, and chemical environment (or the chemical composition of the original material) have impressed quite distinctive features on the metamorphic derivatives, the nature of the metamorphic facies enables us to trace back the course of metamorphism and to form conclusions concerning the nature of the original material.

The crystalline metamorphic rocks herein discussed are of two facies: (1) the cordierite-garnet-sillimanite-rocks; and (2) the scapolite-gneisses and the calc-gneisses. Taking the mineral composition, structure, and texture of these rocks into consideration, it is possible to trace the nature of the metamorphism and the facies of the original rock.

The cordierite-garnet-sillimanite-rocks by the nature of their mineral constituents show that they belong to the katazone¹ representatives of Grubenmann and Niggli² formed from pelitic schists. The conditions for the production of these katazone products are high temperature and very great uniform pressure, directed pressure being feeble or absent. The nature of the metamorphism involved is 'load' or static metamorphism; in other words, plutonic metamorphism, which is characterized by the production of anti-stress minerals, of which cordierite and sillimanite preponderate in this rock. The other chief constituents of this rock are biotite and garnet. The garnets occur as small red spots very uniformly distributed and can be considered as a product of metamorphism in the infra-plutonic zone.³

The artificial formation of cordierite and sillimanite in aluminosilicate melts of the general formula $RO.mAl_2O_3.nSiO_2$ has been

¹ G. W. Tyrrell, *The principles of petrology*, 1926, p. 258.

² U. Grubenmann and P. Niggli, *Die Gesteinsmetamorphose*, 1924, pp. 375–390.

³ L. L. Fermor, *Garnet as a geological barometer*, *Rec. Geol. Survey India*, 1913, vol. 43, pp. 41–44.

studied by J. Morozewicz (1898). He found that if Fe and Mg are absent and if n is greater than 6, then sillimanite or sillimanite and corundum will form. When Fe and Mg are present and with n less than 6, then spinel or spinel and corundum are produced; with n greater than 6, the magnesia and excess of alumina give rise to cordierite or cordierite and spinel.

In a study of the paragenesis of the system $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$ by the investigation of melts, Grubenmann and Niggli show that cordierite, sillimanite, and quartz are formed below 1425° . The temperature for the formation of sillimanite was found to be 1000° at a pressure of one atmosphere, and $1320\text{--}1380^\circ$ when formed from kyanite. It is also observed that in a magma or a sediment at great depth the assemblage quartz, sillimanite, and enstatite will not be stable, and may be transformed to the system cordierite, quartz, and sillimanite:



The paragenesis in the katazone of the system $\text{MgO-Al}_2\text{O}_3\text{-CaO}$, with quartz as a fourth phase, is also dealt with in figs. 91 and 92 of Grubenmann and Niggli (loc. cit.). With the addition of iron and alkalis (in feldspars), alkalis and water promote the formation of biotite if there is high alumina content. So the first field of the katazone paragenesis consists of quartz, potash-feldspar, biotite, plagioclase, sillimanite, and cordierite. The ilmenite in the katazone goes in the presence of any available lime to sphene and magnetite.

Thus the cordierite-garnet-biotite-sillimanite-gneiss presents all the features of katazone paragenesis, while the presence of garnet indicates infra-plutonic metamorphism. Since the garnet contains inclusions of quartz and biotite, it must be considered to have formed as a later product of recrystallization. Considering the banded and foliated structure, and the elongated and longitudinally fractured garnets and quartz grains, it is evident that there has been a strong pressure at right angles to the direction of foliation in this rock. Thus these rocks show that there has been thermal or infra-plutonic metamorphism followed or accompanied by regional or dynamo-thermal metamorphism.

The effects of these two forms of metamorphism on the accompanying calc-gneisses may now be considered. The mineral constituents of these rocks comprise quartz, calcite, scapolite, pyroxene, a little feldspar, apatite, sphene, and iron-ore. The origin of scapolite is not

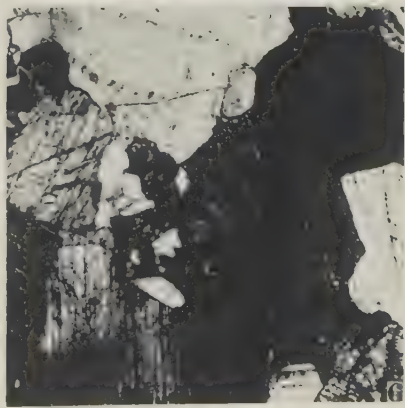
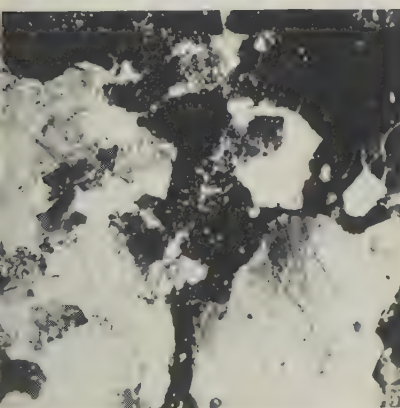
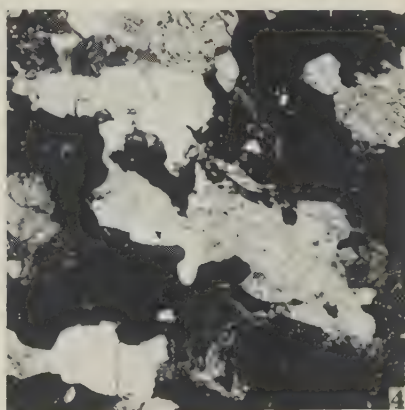
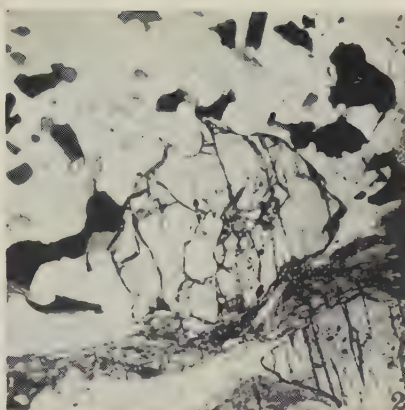
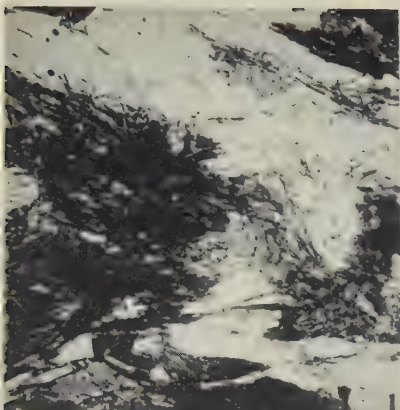
always easy to trace. In the case of the crystalline limestone of Burma, Professor J. W. Judd attributed it to the alteration of the plagioclase felspar. It has also been attributed to contact pneumatolytic reactions between igneous rocks and limestones. Sir T. H. Holland¹ in his paper, 'On the origin and growth of garnets', has mentioned that scapolite is conspicuous amongst the new minerals, where earth movements have been preceded by the production of sodium chloride inclusions along the twin-planes of the felspars. Mr. Vredenburg² has recorded the production of scapolite from the felspar due to the action of chlorine vapours passing along a fissure during the cooling of the rock in a trap dike in the Godavery district.

In the case of the calc-gneisses of the Central Provinces a limited contact-metamorphism has been attributed to 'lit-par-lit' intrusion of an acid magma. In the Coimbatore district, thin veins of pegmatite and quartz imply the proximity of an igneous intrusion, though no 'lit-par-lit' intrusion is found. On examining thin sections of these rocks for the crystalloblastic order, scapolite is one of the earliest minerals to form; it occurs as idioblastic crystals and as inclusions in the pyroxenes and the felspar. It forms a considerable part of the rock, and is very fresh and undecomposed. So it is difficult to prove that it has been formed by the alteration of a plagioclase felspar. The only explanation is that it must have been formed when the limestone was affected by thermal metamorphism, in which it must have been involved, as is proved by the local presence of garnets. The structure of the rock, the joints due to pressure and folding, orientation of the garnet on the rock surface, and the mineral arrangement in the rock sections as revealed by the microscope, show that dynamo-metamorphism or regional metamorphism had also a share in the metamorphism of these rocks. As a consequence, quartz grains and calcite show strain polarization, the quartz and scapolite are elongated in the direction of foliation, and the former has developed longitudinal cracks. The additional elements required for the formation of such minerals as scapolite, felspars, biotite, &c., must have been either present in the original rocks or introduced during the plutonic phase of the metamorphism.

Acknowledgements.—My best thanks are due to Professor W. W. Watts for kindly affording me the necessary facilities at the Imperial

¹ T. H. Holland, Rec. Geol. Survey India, 1896, vol. 29, p. 23.

² E. W. Vredenburg, Ibid., 1904, vol. 31, p. 233.



L. A. NARAYANA IYER: GNEISSES FROM COIMBATORE.

College of Science and Technology, London, for carrying out this work. I am also indebted to Professor C. G. Cullis, Dr. Alfred Brammall, and other members of the staff, who have always rendered me all the necessary help. I express my sincere thanks to Dr. L. L. Fermor of the Geological Survey of India for going through my original paper and for many useful and instructive suggestions. I am much indebted to the authorities of the Cambridge University Press for kindly lending the original photograph for fig. 2.

EXPLANATION OF PLATE V.

Gneisses from Coimbatore, Madras. Crossed nicols (except fig. 2).

Magnification 17 diameters.

- FIG. 1. 'Tabloid' aggregate of sillimanite, cordierite, quartz, graphite, &c. (Specimen no. 10, p. 124.)
2. Cordierite-garnet-sillimanite-gneiss (madukarite), showing cordierite, garnet, sillimanite, biotite, and quartz. (No. 9, p. 125.)
 3. Cordierite-garnet-sillimanite-gneiss (madukarite), showing poikilitic plates of cordierite with inclusions of quartz and biotite. (No. 9, p. 125.)
 4. Scapolite-gneiss, containing diopside, large plates of scapolite showing cleavage, quartz, sphene, &c. (p. 126.)
 5. Recrystallized calc-gneiss, consisting mostly of feldspars showing undulose extinction, quartz, and diopside. The feldspars have 'quartz de corrosion' (myrmekite) along their edges. (p. 127.)
 6. Coarse-grained calc-gneiss, consisting mostly of crystalline calcite, in which diopside, hornblende, and sphene are formed. (p. 128.)
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A relation between the density and refractive index of silicate glasses, with application to the determination of imitation gem-stones.

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IT has long been possible to identify readily many minerals by means of density and refractive index determinations, and the chemical composition also can often be approximately deduced. Tilley¹ has shown that it is practicable to determine any natural glass by this method and he succeeded in separating the natural glasses into groups characterized by certain limits of specific refractivity. As far as the author is aware, no such systematic method has been described for distinguishing the artificial glasses one from the other, and it is these glasses that we are concerned with in attempting to determine the approximate composition of an imitation gem-stone without the aid of chemical analysis.

The glasses employed in the manufacture of imitation gem-stones may be divided up into the following classes :

(1) Bottle and window-glass; constituents, CaO , Na_2O or K_2O , SiO_2 , Fe_2O_3 , TiO_2 , &c.

(2) Strass or lead glass; constituents, PbO , Na_2O or K_2O , SiO_2 .

Glasses of these two kinds date back to very early times. More recent materials are :

(3) Opal glasses; constituents same as (1), but also CaF_2 , SnO_2 , or phosphates.

(4) Borosilicate glasses; constituents, B_2O_3 , Na_2O or K_2O , SiO_2 .

(5) Lead glass in which the monovalent base Na_2O or K_2O is replaced by thallium oxide.

(6) Barium glasses designed primarily for optical work have been utilized for the cheaper types of cut-glass table ware. It is only

¹ C. E. Tilley, *Min. Mag.*, 1922, vol. 19, p. 275.

slightly inferior in brilliancy to the lead cut-glass ware. Cheap imitation gems of barium glass are perhaps also to be found on the market.

(7) Glasses similar in composition to gem-stones but non-crystalline, a notable example being an emerald glass. This class is to be carefully distinguished from the artificial gem-stone, which is not only similar in composition but is also crystalline.

The distinction between classes (1) and (2) is no difficult matter. The possible variations in composition within each class, however, show one important difference. The percentage of colouring material needed in lead glass imitations is very small. Density and refractive index determinations can tell us the approximate percentage of PbO , but nothing about the colouring constituent; this we may be able to judge from the colour. Class (1) differs materially in this respect. The amounts of Fe_2O_3 , TiO_2 , &c., used in colouring window-glass imitations are sufficient to affect materially the density and refractive index. Some method of distinguishing these types is therefore necessary. In addition, the method should be capable of distinguishing the more recent imitations described under classes (3), (4), (5), (6), and (7).

We intend to base our method on determinations of density and refractive index just as Tilley did in his work on the natural glasses. This is because these are physical properties generally capable of rapid and accurate measurement. It must be remembered, however, that the optical dispersion of a glass is sensitive to small changes in chemical composition, and indeed for optical work this property is of paramount importance. There may be cases where, in order to distinguish one glass from another with certainty, dispersion measurements must be used. An example of this is the distinction between a potassium lead glass and thallium lead glasses containing not more than 10 % Tl_2O (see below). In general, however, this more lengthy determination can be dispensed with. By plotting the density of natural glasses against their specific refractivity Tilley was able to group these glasses according to their chemical composition. It was soon found during the course of the present work that with the artificial glasses only partial success awaits such procedure. When, for instance, a series of various optical glasses is plotted in this way it is possible to distinguish only the lead glasses from the calcium glasses. The barium glasses, however, are confused with the lead glasses, it is difficult to separate the borosilicates, and no definite separation

within the calcium group owing to the presence of other oxides is apparent. This indicated, therefore, that some other method would be necessary in dealing with imitation gem-stones. Limiting the determinations to density and refractive index, is it possible to discover a relation involving these two variables which indicates the composition of any silicate glass more clearly than does the specific refractivity? It is obviously important to study families of simple glasses to discover any fundamental relation.

Prior to the Great War this country imported nearly all its optical glass from Germany. The fascinating story of how patient research founded yet another home industry, and how England was able to produce the large quantities of optical glass needed in warfare is to be found among the papers of the Journal of the Society of Glass Technology. C. J. Peddle¹ gives a most interesting summary of this work, and indeed it is his systematic researches in various glass families that supplied the material for the present paper. It should be mentioned that the United States of America was confronted with a similar, though less urgent problem, and F. E. Wright² is responsible for pioneer work on optical glass in that country. Naturally Peddle's and Wright's work have much in common, but the latter's preference for graphical representation of results, as opposed to tabulated data, renders his experimental values less accessible.

We will proceed at once, then, to a brief description of Peddle's work. He examined the physical and chemical properties of the simple glasses $100\text{SiO}_2.x\text{Na}_2\text{O}$, x varying from 20 to 100 molecules.³ This was also done for two potassium silicate glasses and two sodium potassium silicate glasses. He then proceeded to examine glasses of the type $100\text{SiO}_2.40\text{M}_2\text{O}.x\text{NO}$ and $100\text{SiO}_2.20\text{M}_2\text{O}.x\text{NO}$ where M is sodium or potassium, N is calcium, barium, or lead, and x varies from 5 to 40 molecules.⁴ Data were also obtained in each case for the glasses $100\text{SiO}_2.20\text{Na}_2\text{O}.20\text{K}_2\text{O}.x\text{NO}$ and $100\text{SiO}_2.10\text{Na}_2\text{O}.10\text{K}_2\text{O}.x\text{NO}$. Peddle gives values of the density, refractive index, dispersion, &c., for each glass sample made up, but it must be remembered that the composition of the glass differs, probably only slightly, from the 'batch' composition. Data on analysed glasses are very scarce, and it is evident that Peddle's work suffers in this

¹ C. J. Peddle, Journ. Soc. Glass Tech., 1920, vol. 4, p. 225.

² F. E. Wright, Journ. Amer. Ceramic Soc., 1920, vol. 3, p. 783.

³ C. J. Peddle, Journ. Soc. Glass Tech., 1920, vol. 4, pp. 20, 46, 59.

⁴ Ibid., p. 299, and 1921, vol. 5, p. 201.

respect and necessarily so, owing to the urgency of the problems he attacked.

The present work has for its object the speedy identification of any silicate glass by determining the density, correct to 0.005 gm. per c.c., and the refractive index correct to 0.0005. It is also hoped to obtain some idea as to its composition by this procedure. In referring to Peddle's work, then, on simple glass families we are primarily interested in his density and refractive index determinations. For each glass family he gives six determinations; in each case I have plotted the refractive index against the density correct to the limits specified above. Any one glass family thus plotted gives a straight line and each family gives a line whose slope is different from all the others. In all, twenty lines were plotted from Peddle's data; three typical lines are shown in fig. 1. The requisite data for plotting all the lines are given in Table I, which also includes Larsen's data for the albite-anorthite glasses and enstatite-wollastonite glasses.¹ The three lines plotted in fig. 1 converge approximately to the same point, and the same result is true if all the lines be plotted together on the same graph. It might thus appear that if we were given the density and refractive index of an unknown glass we could arrive at its approximate composition by judging to which of the lines it fell nearest. This is the case for glasses whose density exceeds 3.00, but for values less than this it is difficult to distinguish one line from another owing to this property of convergence. Supposing now we find the coordinates, N , D , of this point of convergence for all the glass lines. Then if n and d be the refractive index and density of any one glass given in Table I, $(n-N)/(d-D)$ will give the slope of the line on which the given glass lies. By the slope of any glass line as plotted in fig. 1 is meant the increase in refractive index per unit increase in density. Thus $(n-N)/(d-D)$ should be constant for any one family. It must be emphasized that the convergence to one point of all these lines is only approximate. Thus the ratio $(n-N)/(d-D)$ is only approximately constant and only approximately equal to the slope of the appropriate line, particularly for values of n and d approaching closely to N and D . We now proceed to find N and D as accurately as possible. For the three lines plotted in fig. 1, N and D can be read off directly, but for a large number of lines approximately convergent such a procedure is more difficult. It is simpler to plot each line separately and measure directly both its slope and the

¹ E. S. Larsen, Amer. Journ. Sci., 1909, ser. 4, vol. 28, p. 263.

TABLE I. (Data from C. J. Peddle and E. S. Larsen.)

<i>Calcium glasses.</i>								
100SiO ₂ .40Na ₂ O. xCaO.			100SiO ₂ .20Na ₂ O. xCaO.		100SiO ₂ .40K ₂ O. xCaO.		100SiO ₂ .20K ₂ O. xCaO.	
x.	n.	d.	n.	d.	n.	d.	n.	d.
5	1.5110	2.503	1.4970	2.412	1.5125	2.488	1.5011	2.420
10	1.5189	2.533	1.5088	2.458	1.5179	2.513	1.5081	2.450
15	1.5259	2.559	1.5192	2.499	1.5229	2.535	1.5151	2.478
20	1.5327	2.584	1.5279	2.537	1.5277	2.555	1.5223	2.505
30	1.5442	2.629	1.5435	2.603	1.5379	2.594	1.5355	2.555
40	1.5540	2.667	1.5573	2.659	1.5475	2.630	1.5491	2.601

<i>Lead glasses.</i>								
100SiO ₂ .40Na ₂ O. xPbO.			100SiO ₂ .20Na ₂ O. xPbO.		100SiO ₂ .40K ₂ O. xPbO.		100SiO ₂ .20K ₂ O. xPbO.	
5	1.5299	2.710	1.5186	2.628	1.5290	2.681	1.5201	2.616
10	1.5558	2.912	1.5448	2.911	1.5510	2.868	1.5480	2.849
15	1.5761	3.112	1.5691	3.152	1.5710	3.043	1.5707	3.089
20	1.5927	3.282	1.5930	3.368	1.5910	3.175	1.5941	3.290
30	1.6219	3.543	1.6272	3.690	1.6230	3.474	1.6284	3.640
40	1.6472	3.756	1.6571	3.940	1.6508	3.728	1.6596	3.942

<i>Barium glasses.</i>								
100SiO ₂ .40Na ₂ O. xBaO.			100SiO ₂ .20Na ₂ O. xBaO.		100SiO ₂ .40K ₂ O. xBaO.		100SiO ₂ .20K ₂ O. xBaO.	
5	1.5155	2.604	1.5037	2.557	1.5195	2.619	1.5080	2.565
10	1.5280	2.738	1.5202	2.708	1.5285	2.718	1.5203	2.681
15	1.5404	2.864	1.5357	2.853	1.5381	2.803	1.5317	2.798
20	1.5510	2.966	1.5483	2.987	1.5479	2.904	1.5437	2.922
30	1.5679	3.134	1.5698	3.203	1.5644	3.079	1.5652	3.143
40	1.5775	3.248	1.5895	3.407	1.5755	3.205	1.5838	3.308

<i>Sodium and potassium glasses.</i>								
100SiO ₂ .xNa ₂ O.			100SiO ₂ .xK ₂ O.					
x.	n.	d.	x.	n.	d.	x.	n.	d.
20	1.4851	2.353	70	1.5118	2.535	20	1.4937	2.388
30	1.4952	2.413	80	1.5139	2.544	—	—	—
40	1.5015	2.457	90	1.5155	2.555	40	1.5073	2.465
50	1.5056	2.495	100	1.5168	2.560	—	—	—
60	1.5090	2.521	—	—	—	—	—	—

Albite-Anorthite glasses.

Composi- tion.	n.	d.
Ab	1.4890	2.382
Ab ₂ An ₁	1.5166	2.483
Ab ₁ An ₁	1.5307	2.533
Ab ₁ An ₂	1.5452	2.591
Ab ₁ An ₅	1.5600	2.648
An	1.5755	2.700

Enstatite-Wollastonite glasses.

MgSiO ₃ .			MgSiO ₃ .		
%.	n.	d.	%.	n.	d.
0	1.6280	2.904	46.36	1.6073	2.854
5	1.6262	2.899	60	1.6007	2.834
14.74	1.6223	2.891	70	1.5960	2.821
26	1.6174	2.881	90	1.5851	2.780
36	1.6122	2.872	95	1.5822	2.777
40	1.6105	2.859	100	1.5801	2.758

intercept of the line with the n axis. Table II shows the measured values of the slope a and the intercept b for each line. The general equation to any line as plotted in fig. 1 can then be expressed by

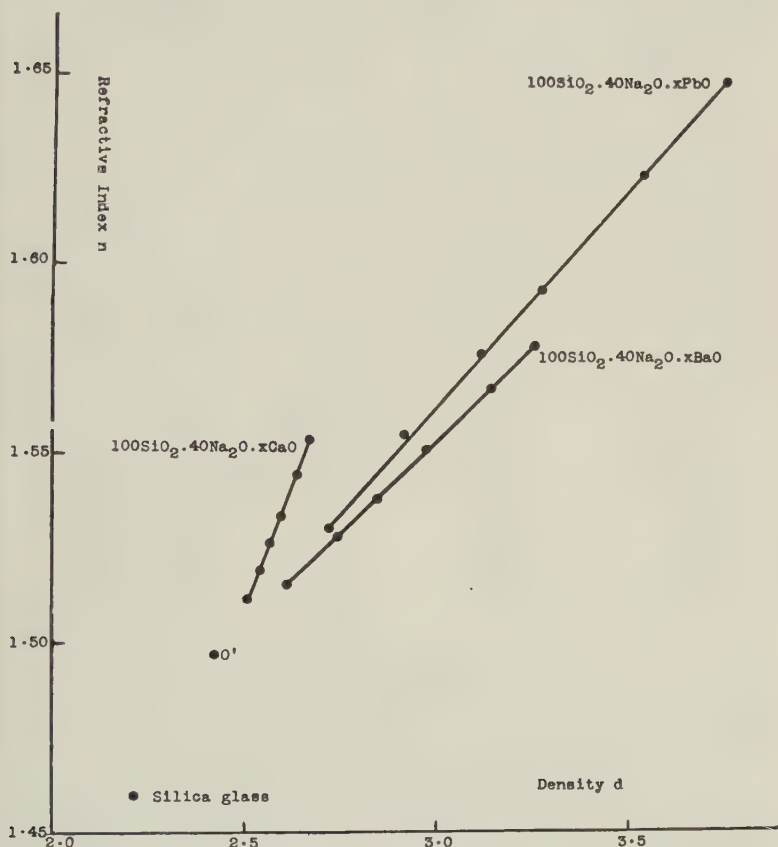


FIG. 1. Graph plotting refractive index n and density d of glass families.

$n = ad + b$. If this line passes through the point of convergence whose co-ordinates we have assumed to be N, D , then

$$N = aD + b. \quad (1)$$

This relation is true for each pair of a and b values listed in Table II providing the appropriate line passes through the point of convergence. Thus

$$a = -\frac{b}{D} + \frac{N}{D}, \quad (2)$$

that is, plotting a against b should give a straight line whose slope (da/db) is equal to $-1/D$ and whose intercept on the a axis is equal to N/D . Fig. 2 shows such a graph for all a and b values, from which it is clear to what degree of accuracy the a and b values for each family conform to equation (1). Further, it is now possible from the slope of the line in fig. 2 and its intercept with the a axis to measure

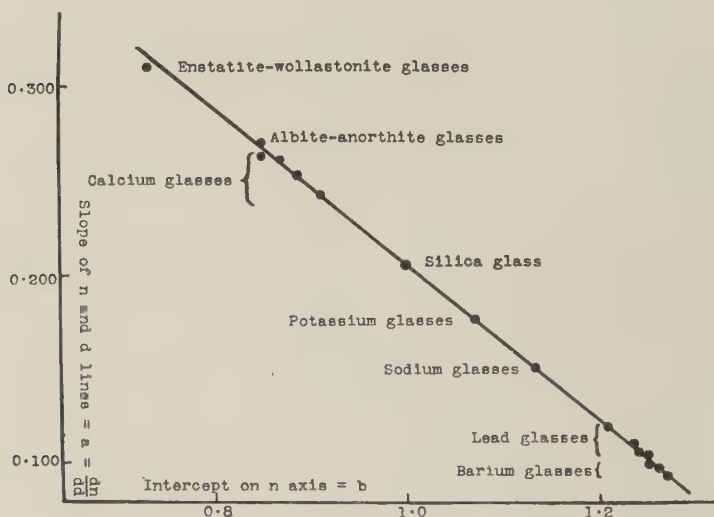


Fig. 2. Graph plotting dn/dd and intercept on n axis for glass families.

directly the values of N and D ; we obtain $N = 1.497$; $D = 2.43$. This point O' so deduced has been marked in fig. 1.

Table II contains all the directly determined values of a and b ; in addition, values of b calculated from the now known values of N and D and equation (1) have also been given. The straight line relations that have thus been obtained are not surprising if we regard glasses as solid solutions and 1.497 and 2.43 as the values of refractive index and density for the 'parent substances' of all these glasses. Now we know that Peddle gradually added equal molecular proportions of CaO , PbO , or BaO to a group consisting of either $100\text{SiO}_2 \cdot 40\text{M}_2\text{O}$ or $100\text{SiO}_2 \cdot 20\text{M}_2\text{O}$, where M is Na or K . If we tabulate the n and d values of these four 'parent substances' as below and average them it is obvious we have an explanation of the values 1.497 and 2.43 obtained from graph 2. The agreement is as exact as we can expect.

Glass composition.	Refractive index, n .	Density, d .
100 SiO ₂ .20Na ₂ O	1.4851	2.353
100 SiO ₂ .40Na ₂ O	1.5015	2.457
100 SiO ₂ .20K ₂ O	1.4937	2.388
100 SiO ₂ .40K ₂ O	1.5073	2.465
Average	1.497	2.42

TABLE II. (Data for plotting in fig. 2.)

Glass family.	Slope of line $a = dn/dd$.	Intercept b .	Calculated intercept $b^1 = N - aD$.
100SiO ₂ .20-100Na ₂ O	0.150	1.132	1.135
100SiO ₂ .20-40K ₂ O	0.176	1.073	1.071
100SiO ₂ .20Na ₂ O.xCaO	0.243	0.911	0.910
100SiO ₂ .40Na ₂ O.xCaO	0.264	0.851	0.858
100SiO ₂ .20K ₂ O.xCaO	0.261	0.869	0.866
100SiO ₂ .40K ₂ O.xCaO	0.252	0.885	0.887
100SiO ₂ .40Na ₂ O.xPbO	0.109	1.236	1.235
100SiO ₂ .20Na ₂ O.xPbO	0.105	1.239	1.244
100SiO ₂ .40K ₂ O.xPbO	0.119	1.210	1.211
100SiO ₂ .20K ₂ O.xPbO	0.104	1.250	1.247
100SiO ₂ .40Na ₂ O.xBaO	0.094	1.270	1.271
100SiO ₂ .20Na ₂ O.xBaO	0.099	1.254	1.257
100SiO ₂ .40K ₂ O.xBaO	0.098	1.263	1.262
100SiO ₂ .20K ₂ O.xBaO	0.100	1.252	1.254
Albite-anorthite	0.269	0.848	0.846
Enstatite-wollastonite	0.309	0.730	0.746

Having found N and D as accurately as possible, $(n - N)/(d - D)$ can now be calculated for any glass and plotted against n or d . For any one family of glasses such a procedure should, of course, result in a horizontal straight line whose ordinate is equal to the a value for the family as given in Table II. There is a simple graphical method of plotting $(n - N)/(d - D)$ against n or d which will now be described. Choosing the former alternative we plot values of n as abscissae and values of $(n - N)/(d - D)$ as ordinates. We now want to find how n varies with $(n - N)/(d - D)$ for various fixed values of d , say 2.5, 2.6, 2.7, &c.

Now $(n - N)/(d - D) = a$; $\therefore n = (d - D)a + N$.

Substituting the values for N , D , and d we get a series of equations:

$$\begin{aligned} n &= (2.5 - 2.43)a + 1.497, \\ n &= (2.6 - 2.43)a + 1.497, \\ n &= (2.7 - 2.43)a + 1.497, \text{ \&c.,} \end{aligned}$$

each of which represents a straight line passing through the point 1.497 on the n axis. Choosing a convenient value, say 0.4, for a , we get $n = 1.525, 1.565, 1.605$, &c. Thus we merely have to subdivide the horizontal line $a = 0.4$ and join each point to the point $n = 1.497$ on the n axis. We then have a system of lines radiating from one point each corresponding to a given density. Fig. 3 illustrates such a system; any glass whose refractive index and density are known can now be readily plotted and its a value read off directly. Peddle's data have been plotted in this way in fig. 3. For any one family, the glasses whose values of n and d approach 1.497 and 2.43 no longer lie on a horizontal line, but lie on a curve. The reason for this is not far to seek. From the expression $(n - 1.497)/(d - 2.43)$, as both numerator and denominator become smaller, any small irregular variation of n or d or any small error in the values of the fixed constants 1.497 and 2.43 will greatly affect the value of a . Finally, when $n = 1.497$ and $d = 2.43$, a is indeterminate, i. e. a glass corresponding to these values when plotted in the graph can lie anywhere on the vertical line $n = 1.497$.

Before proceeding to the application of this method of plotting for determining imitation gem-stones, a brief explanation will be given of the significance of the slope of any n and d line as plotted in fig. 1. Peddle and Larsen both found that the refractive indices and the specific volumes are approximately additive for glasses. It can thence be shown very simply that the relation between the refractive indices and densities of a series of glasses should be sensibly linear, and, moreover, the slope of any line is obviously equal to the difference of the refractive indices of the end-components divided by the difference of the densities of the end-components. As an example let us consider the calcium glasses studied by Peddle. The refractive index and density of one end-component we know to be approximately 1.497 and 2.43. The values for calcium silicate glass from Larsen's work are 1.628 and 2.904. If we assume this as the other end-member for the calcium glasses we shall be ignoring the sodium or potassium oxides present. However $(1.628 - 1.497)/(2.904 - 2.42) = 0.27$. This calculated value is remarkably close to the range of values given in Table II for calcium, namely 0.243 - 0.264.

We have found that the plotting of $(n - N)/(d - D)$ against n is a very suitable one for simple glasses studied by Peddle. It is natural to attempt an application of this method for determining more com-

plex glasses. Since imitation gem-stones are made from various glasses whose 'parent substance' is SiO_2 rather than $100\text{SiO}_2 \cdot 20\text{-}40\text{M}_2\text{O}$ we will plot $(n - 1.460)/(d - 2.21)$ against n , where 1.460 and 2.21 are the refractive index and density of silica glass. There is

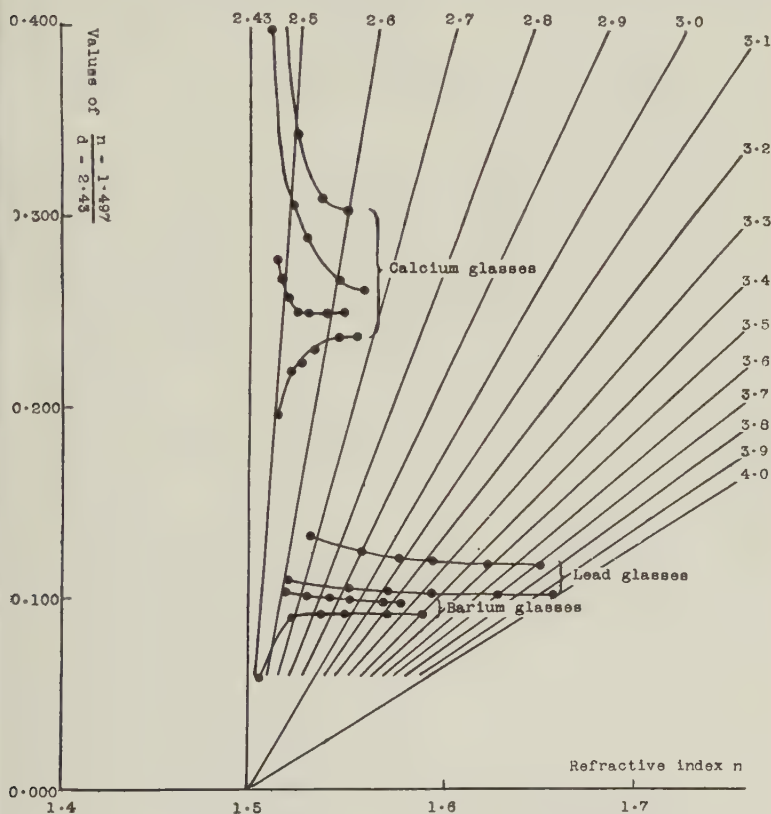


FIG. 3. Graph plotting $(n - 1.497)/(d - 2.43)$ and n for glass families.

an additional reason for adopting these lower values for N and D . Quite a large number of imitation gem-stones have refractive indices in the neighbourhood of 1.497. From fig. 3 it is obvious that such glasses are not well separated. It would be better to have the indeterminate region farther to the left. This has been achieved by changing N and D to the values for silica glass. This method possesses an advantage in that it separates the glasses into groups more satisfactorily than plotting the specific refractivity as was done

by Tilley. Incidentally such a method need involve no calculation; the plotting can be done graphically in the way described above.

Before plotting any unknown glass the simple glass families were marked out so that definite areas could be assigned to the calcium, barium, and lead glasses. Naturally, plotting the modified expression $(n - 1.46)/(d - 2.21)$ against n does not lead to a system of horizontal straight lines as in fig. 3, but it is possible to mark out the above-mentioned areas, and the lead and barium lines are only slightly inclined to the horizontal.

The borosilicate glasses present a different type of problem from most glasses. English and Turner¹ have studied a series of sodium borosilicate glasses and they find that neither the specific volumes nor the specific refractivities can be considered as additive. If the density of each glass be plotted against the refractive index not only are the curves obtained far from linear but they possess a point of inflexion. If we plot $(n - 1.46)/(d - 2.21)$ against n for these glasses, however, on the same graph as we have marked out areas for the silicate glasses (fig. 4), then a definite area is obtained for the borosilicates, although, of course, there is no approach to horizontal alinement.

Having now obtained as it were a general key to glass composition for some of the more important glass constituents we proceed to test its use and accuracy upon glasses of known composition. For this purpose we make use of the data on optical glasses listed by G. W. Morey² and F. E. Wright,³ which are reproduced in Table III and plotted in fig. 4. To keep this graph as clear as possible only the limits of each group have been marked. There would be no object in showing a whole range, for instance of lead glasses, all close to each other. With the exception of glasses containing both barium and lead the separation of the different types is well marked. It may be noted that the natural glasses plotted in this way separate out just as well as in the Tilley plot.

We are now in the position to use fig. 4 for the determination of imitation gem-stones. The particular imitations examined comprised about twenty-five typical specimens very kindly lent to me by the late Mr. B. J. Tully and a varied collection in the Mineral Department of the British Museum (Natural History); in all between

¹ S. English and W. E. S. Turner, *Journ. Soc. Glass Tech.*, 1923, vol. 7, p. 155.

² G. W. Morey, *International Critical Tables*, 1927, vol. 2, p. 102.

³ F. E. Wright, *Journ. Amer. Ceramic Soc.*, 1920, vol. 3, p. 783.

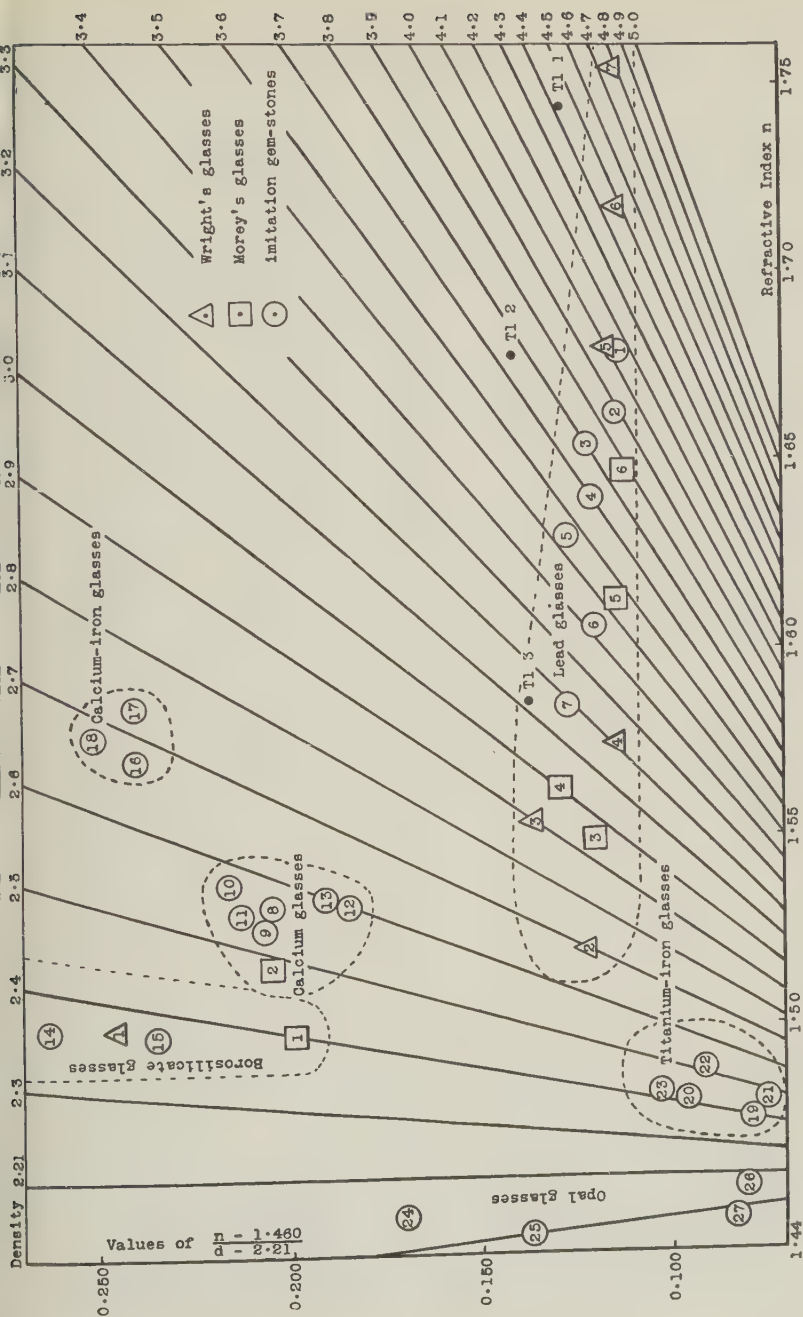


Fig. 4. Graph plotting $(n - 1.460) / (d - 2.21)$ and n for imitation gem-stones and optical glasses.

TABLE III. (Data from F. E. Wright and G. W. Morey.)

Graph No. (Figs. 4 & 5).	Original No. of Glass.	n_D .	$\frac{n_F - n_C}{n_D - 1}$.	d .
1	Wright, 12	1.4997	0.0155	2.37
1	Morey, 5	1.4980	0.0153	2.40
2	„ 20	1.5155	0.0165	2.48
2	Wright, 47	1.5202	0.0194	2.70
3	Morey, 48	1.5491	0.0220	2.95
3	Wright, 53	1.5537	0.0222	2.90
4	Morey, 55	1.5632	0.0233	3.07
4	Wright, 56	1.5752	0.0244	3.22
5	Morey, 92	1.6134	0.0271	3.55
6	„ 101	1.6469	0.0297	3.87
5	Wright, 78	1.6801	0.0316	4.10
6	„ 80	1.7174	0.0339	4.49
7	„ 82	1.7541	0.0364	4.78
8	„ 83	1.7782	0.0377	4.99
9	„ 84	1.8904	0.0448	5.83
10	„ 86	1.9053	0.0461	5.94
11	„ 87	1.9626	0.0508	6.33

Glass No.	SiO ₂ .	B ₂ O ₃ .	K ₂ O.	Na ₂ O.	CaO.	PbO.
Wright, 12 ¹	72.0	12.0	—	11.0	—	—
Morey, 5	59.5	21.5	14.4	—	—	—
„ 20	69.5	—	19.0	—	11.1	—
Wright, 47 ¹	68.7	—	—	15.7	—	13.3
Morey, 48 ¹	60.6	—	13.9	—	—	22.5
Wright, 53	59.3	—	8.0	5.0	—	27.5
Morey, 55	55.9	—	11.1	—	—	32.9
Wright, 56	53.7	—	8.3	1.0	—	36.6
Morey, 92	48.0	—	1.2	5.2	—	45.1
„ 101	40.6	—	7.5	—	—	51.5
Wright, 78	38.0	—	5.0	—	—	56.8
„ 80	33.7	—	4.0	—	—	62.0
„ 82	28.4	—	2.5	—	—	69.0
„ 83	27.3	—	1.5	—	—	71.0
„ 84	22.0	—	—	—	—	78.0
„ 86	20.0	—	—	—	—	80.0
„ 87	18.0	—	—	—	—	82.0

¹ Wright 12 contains also Al₂O₃ 5 %; Wright 47 also ZnO 2.5 %; Morey 48 also BaO 2.5 %.

seventy and eighty imitations were examined. The majority, of course, consist of the commonplace window-glass and lead glass imitations, and only a few limiting cases of such glasses are listed in Table IV and plotted in fig. 4. The density of each specimen was determined by weighing in air and in toluene. The final corrected value, as plotted and tabulated, being the specific gravity in vacuo

TABLE IV. (New determinations made on imitation gem-stones.)

Graph No. (Fig. 4). Colour.	n_D .	d .	Graph No. (Fig. 4). Colour.	n_D .	d .
1 Peridot-green	1.679	4.12	2 Pale yellow	1.662	3.97
3 Purple	1.654	3.79	4 Opal-green	1.640	3.70
5 Citron	1.630	3.53	6 Emerald-green	1.606	3.42
7 Red	1.585	3.18	8 Lemon-yellow	1.532	2.56
9 Pale green	1.526	2.53	10 Sea-green	1.538	2.57
11 Colourless	1.530	2.55	12 Smoky	1.532	2.60
13 Smoky	1.534	2.60	14 Pale blue	1.500	2.36
15 Pale blue	1.497	2.37	16 Sage-green	1.571	2.67
17 Sea-blue	1.585	2.73	18 Dark green	1.577	2.68
19 Brown	1.475	2.40	20 Pale amber	1.480	2.42
21 Brown	1.479	2.46	22 Very dark brown	1.488	2.52
23 Sherry-brown	1.482	2.42	24 Opal-white	1.450	2.15
25 Opal-white	1.445	2.10	26 Opal-yellow	1.457	2.17
27 Cloudy-white	1.449	2.07			

Nos. 1, 14, 15, 16, 17, 18, and 22 were kindly lent by the late Mr. B. J. Tully. No. 11 is a bottle-glass. No. 23 is B.M. 91601. The remainder are registered as B.M. 91599.

at 4° C. The refractive index was measured for sodium-light with the Abbé-Pulfrich refractometer. We have endeavoured to plot in fig. 4 typical examples of each important class; the data for each point on the graph are listed in Tables III and IV and p. 152. It may be added that examples of modern cheap imitation jewellery, glasses said to be more transparent to ultra-violet rays than window-glass, iridescent glass imitations, &c., have also been examined.¹ Fig. 4 should be capable of development when further systematic work on glass families has been published.

Each group of glasses will now be considered briefly. Lead glass imitation gem-stones with the highest and lowest values of refractive index observed in this work have been plotted, and intermediate ones are given at equal intervals. If all the numerous lead glass imitations are plotted it is interesting to note that the approximate centre of gravity of the swarm is the optical glass whose composition (see Table III) closely approximates to that of strass. Fig. 4 does not include the optical glasses Wright 8, 9, 10, and 11 containing a high percentage of lead. These glasses fall on an approximately horizontal line to the right of fig. 4 and level with Wright 5, 6, and 7. No barium imitations are given; they would fall to the left of the lead area and towards the bottom. The calcium glasses do not need any

¹ C. J. Stahl, *Die Glashütte*, Dresden, 1926, vol. 56, and 1927, vol. 57, gives batch compositions for glasses used in the production of glass jewellery, pendants, beads, and imitation gem-stones.

comment. The position of the calcium-iron glasses is confirmed by the position of the basalt glasses. These may be plotted in from Tilley's data and it is then seen that the imitations 16, 17, and 18 fall on the edge of the basalt field. Hence we can conclude that these are made from ordinary window-glass containing a large percentage of ferric oxide. It is well known that amber-coloured imitations are made from glass containing iron and titanium. All the amber-coloured imitations studied in this work fall into a very definite group and probably justify the labelling of the titanium-iron area in fig. 4. As far as is known data for such glasses do not exist. The opal glasses are situated to the left of the density line 2.21. No separation into groups of this type of imitation has been attempted. The borosilicate glasses are easy to identify by this method of plotting and one ultra-violet ray transmitting glass was found to fall in this group.

A specimen of emerald glass kindly lent me by the Director of the Geological Survey of Great Britain is an exceedingly good imitation as regards colour, and is said to have the 'composition of an anhydrous beryl'. Its density 2.385 and refractive index n_D 1.5256 are very low. The former value suggests a borosilicate glass, but the refractive index is rather high for such a glass. The value of $(n - 1.46)/(d - 2.21)$ is higher for this specimen than for any imitation gem-stone so far examined, viz. 0.360. If fig. 4 be extended to permit this glass being plotted, then it will be found to lie to the right of the borosilicate glasses plotted from English and Turner's data. Dispersion measurements also show that this glass is not a borosilicate. The dispersive power $(n_F - n_C)/(n_D - 1)$ for the emerald glass is 0.0145, whereas for borosilicates it does not fall below 0.0150. The refractive index has been measured by the prism method for the C, D, F, and G' lines in the visible spectrum. The refracted image is not sharp owing to lack of uniformity in the glass; striae are visible to the naked eye. This lack of uniformity is probably why the refractometer determination for n_D is slightly higher, viz. 1.5277.

	n_C .	n_D .	n_F .	$n_{G'}$.	$\frac{n_F - n_C}{n_D - 1}$.	d .
Emerald glass	1.5234	1.5256	1.5310	1.5357	0.0145	2.385
Beryl ¹	...	1.574	—	—	0.0157	—
"	...	1.5734	—	—	0.0174	—
"	...	1.5702	—	—	0.0193	—
"	...	1.5704	—	—	0.0210	—
"	...	1.5818	—	—	0.0218	—

¹ The values for beryl have been taken from A. N. Winchell's dispersion tables, Amer. Min., 1929, vol. 14, p. 125.

The distinction between this emerald glass and the other types of imitations is obviously well marked whether we plot it on fig. 4 or measure its dispersive power and plot it on fig. 5. It is interesting, however, to speculate on its actual composition. Greville Williams,¹ over fifty years ago, fused emeralds with the oxyhydrogen blowpipe and found that their density decreases from 2.70 to 2.40. He also succeeded in preparing beryl glasses by fusing together a mixture of the same composition as beryl. He successfully coloured these glasses by the addition of chromic oxide (green), cobalt oxide (blue), and didymium oxide (pink). He gave 2.42 as the density of his artificial glass. It is quite probable, then, that the emerald glass we are studying actually has the 'composition of an anhydrous beryl'. Its colour, of course, is due to the presence of a small amount of chromic oxide. A series of beryllium glasses has recently been studied by Lai and Silvermann.² They vary in density and refractive index from 2.4168 to 2.4885 and 1.5081 to 1.5265 respectively. When plotted on fig. 4 they fall between the borosilicates and the calcium glasses; $(n - 1.460)/(d - 2.21)$ varies from 0.220 to 0.250.

Data on thallium glass are very scanty. It was therefore decided to make up some samples of known composition in order to discover whether lead glass imitations containing thallium could be distinguished from the ordinary lead glass counterfeits. The four glasses were made up to have the molecular formulae $100\text{SiO}_2.20\text{K}_2\text{O}.20\text{Tl}_2\text{O}.20\text{PbO}$, $100\text{SiO}_2.10\text{K}_2\text{O}.10\text{Tl}_2\text{O}.10\text{PbO}$, $100\text{SiO}_2.35\text{K}_2\text{O}.5\text{Tl}_2\text{O}.10\text{PbO}$, and $100\text{SiO}_2.40\text{Tl}_2\text{O}.40\text{PbO}$, but owing to the volatility of thallos oxide the analyses show that the actual composition departs widely from these formulae. In addition to measuring the refractive index and density of these glasses, it was thought advisable to measure the dispersion, and the refractive index was measured for the C, D, and F lines. No. 1 glass is pale blue-green and easily fusible, nos. 2 and 3 are more difficult to fuse and are colourless. No. 3 has shown traces of decomposition since manufacture, probably owing to the high potassium oxide content. These three glasses are all somewhat streaky internally and gave diffuse refracted images. I have not been able to measure their refractive indices to a higher degree of accuracy than the third place of decimals. The fourth glass made up contains no potassium oxide and is easily fusible.

¹ G. Williams, *Proc. Roy. Soc. London*, 1873, vol. 21, p. 409.

² C. F. Lai and A. Silvermann, *Journ. Amer. Ceramic Soc.*, 1928, vol. 11, p. 535.

This glass, by powdering after the first fusion and fusing again, has been rendered reasonably free of striae but is full of minute bubbles. It is violet-brown in colour; such a colour suggests reduction of the lead oxide during fusion, but since the thallium was added as the nitrate after the lead oxide and silica had been melted together, it is difficult to see how reduction could have taken place. The percentage of thallium in this glass is very high, and the bubbles are possibly due to thalious oxide vapour escaping during fusion.

Nos. 2 and 3 glasses are strongly fluorescent in the ultra-violet rays giving a bright primrose-yellow colour, exactly similar to the colour given by thalious carbonate. No. 1 glass is not as strongly fluorescent and gives a darker yellow colour, whilst no. 4 does not appear to react to the rays at all. Many thallium compounds were tried but none with the exception of the carbonate gave the yellow fluorescence. Most gave a dull violet-brown colour, only perceptible when the intensity of the rays was at its maximum. It is well known that a uranium glass containing much lead oxide does not fluoresce. It is possible then that nos. 2 and 3 exhibit fluorescence more than 1 and 4 because they have the lowest lead oxide content. At all events we have yet another method of distinguishing thallium glass imitations of low thallium content from lead glass imitations. All four glasses can be easily scratched with a steel knife and were readily ground and polished to prisms of small angle. Much more accurate measurements were possible on no. 4.

Thallium glasses.

No.	Analyses.				Refractive Indices.			$\frac{n_F - n_C}{n_D - 1}$	Density. <i>d.</i>
	SiO ₂ .	PbO.	Tl ₂ O.	K ₂ O.	C.	D.	F.		
1.	27.17	23.98	36.36	12.07	1.736	1.744	1.766	0.0443	4.42
2.	38.45	18.81	29.38	12.63	1.650	1.657	1.673	0.0342	3.75
3.	36.99	18.06	7.46	37.49	1.581	1.586	1.599	0.0307	3.12
4.	20.83	24.82	55.01	—	1.9276	1.9431	1.9808	0.0564	6.03

For no. 4 glass $n_A' = 1.9126$ and $n_G' = 2.0197$.

It has already been noted that dispersion is an important property for distinguishing glasses one from the other. Wright has separated optical glasses into groups by plotting the dispersive power $(n_F - n_C)/(n_D - 1)$ against n_T . I have reproduced this plot in fig. 5. Wright states that better separation is effected by plotting $(n_D - n_A')/(n_G' - n_F)$ against n_D ; fig. 5, however, is generally an easier and more direct method of plotting, and for this work it is adequate. All four thallium glasses fall well to the right of the lead glasses on

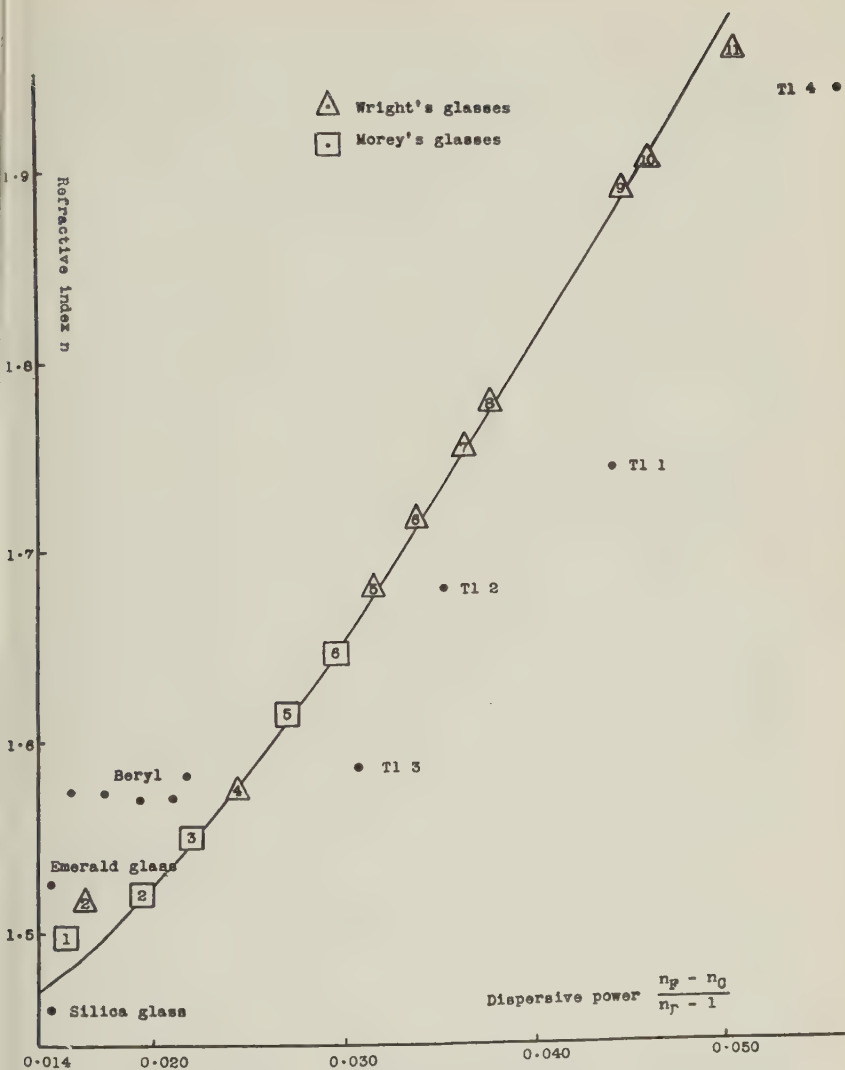


FIG. 5. Graph plotting dispersive power $(n_F - n_C)/(n_D - 1)$ and refractive index n_D for various glasses.

such a graph. In fig. 4, no. 3 thallium glass is very near to the lead area, so that dispersion measurements are in this case a necessary confirmation of the distinction between the two types. Dispersion measurements in general are advised for border-line cases.

The above analyses of the thallium glasses have made possible the evaluation of the density factor of Tl_2O in glass, and also have led to more correct values for the specific refractivities of the constituents. W. L. Baillie's¹ value for the density factor of PbO has been assumed, and that of Peddle for SiO_2 . The specific refractivities of SiO_2 and PbO given by Larsen are assumed to be correct,² since lead glasses of low alkali content agree well; but his value for K_2O has been increased slightly, and that for Tl_2O to a considerable extent.

	SiO_2 .	PbO .	Tl_2O .	K_2O .
Density factor ...	2.20	10.3	9.6	3.00
Specific refractivity ...	0.207	0.137	0.150	0.202
Molecular refractivity...	12.42	30.55	63.6	19.00

In conclusion I should like to thank the Keeper of Minerals, Dr. L. J. Spencer, both for suggesting this interesting problem and for most valuable assistance in presenting the results obtained. To Mr. A. F. Hallimond of the Museum of Practical Geology I am also indebted for help and advice. Mr. M. H. Hey of the Mineral Department kindly made up and analysed the four thallium glasses.

¹ W. L. Baillie, Journ. Soc. Chem. Ind., 1921, vol. 40, p. 141.

² E. S. Larsen, The microscopic determination of nonopaque minerals, 1921, p. 31.

The meteoric stone of Lake Brown, Western Australia.

By G. T. PRIOR, M.A., D.Sc., F.R.S.

Late Keeper of Minerals in the British Museum of Natural History.

[Read June 11, 1929.]

THE discovery of the meteoric stone near Lake Brown,¹ County Avon, South-West Division, Western Australia, was recorded by Dr. Edward S. Simpson in the Annual Progress Report of the Geological Survey of Western Australia for 1921 (1922, p. 53).² The following details concerning the meteorite are taken from that report and from a letter of September 25, 1925, sent by Dr. Simpson with the specimen, weighing 174 grams, which was presented to the British Museum collection by Mr. A. Gibb Maitland, at that time Government Geologist of Western Australia.

The stone was first seen by Mr. N. A. Stuckey in 1919, and was re-discovered later by Mr. H. G. Stokes, by whom it was presented to the Museum of the Geological Survey of Western Australia in Perth, where it is now preserved. As received it measured about $17 \times 15 \times 14$ inches and weighed $21\frac{1}{2}$ lb. (9.75 kg.).³ On one side it shows a few shallow 'thumb-marks' (fig. 1), and on another 'well-marked air-friction striae radiating from a corner' (fig. 2). Its specific gravity, as determined by Dr. Simpson, is 3.505.

Examination of the British Museum specimen (B. M. 1925,1037) showed that the stone has the characters of an intermediate chondrite. The fractured surface is of light grey colour, but is stained in parts with oxide of iron owing to the oxidation which the stone has suffered since its fall. Under the microscope a thin section shows

¹ Lake Brown is a lake and also a railway-station at latitude 31° S., longitude $118\frac{1}{2}^{\circ}$ E., about. On the map of Western Australia by J. Arrowsmith (London, 1863) and in the British Museum 'Catalogue of Meteorites' (1923) the county is given as Carnarvon.

² Separate from Report of the Department of Mines, Western Australia, for 1921, Perth, 1922, p. 123. The entry there reads: 'Lake Brown. A pale grey aerolite with but little metallic nickel iron. Total weight $2\frac{1}{2}$ lbs. Found in 1919 by Mr. Stuckey.'

³ In the original report (loc. cit.) the weight is wrongly given as $2\frac{1}{2}$ lb.

the usual characters of a white or intermediate chondrite, the chondrules being all fragmental and scarcely to be distinguished from the fairly holocrystalline matrix.

Chemical composition.—Dr. Simpson sent with the British Museum specimen a portion weighing 37 grams which, with a view to analysis,



FIG. 1.¹ Meteoric stone of Lake Brown, Western Australia, showing 'thumb-marks'. $\times \frac{1}{8}$.

he had separated into three parts, viz. 32 grams (mostly silicates) which had passed through a 90-mesh sieve, 4.05 grams (mainly metal) which had passed through a 30-mesh sieve, and 0.95 gram (mainly metal) which could not pass the 30-mesh sieve. This material was taken for the analyses, the results of which are given below. By the magnetic comb it was separated into 3.4127 grams attracted and 32.500 unattracted.

¹ Figs. 1 and 2 are reproduced from photographs sent by Dr. E. S. Simpson, and represent the meteorite as first received by the Geological Survey of Western Australia.

The analyses were conducted by the methods described in previous papers. In the attracted the cobalt was separated from nickel by means of α -nitroso- β -naphthol, and in the filtrate nickel was precipitated by dimethylglyoxime. Of the unattracted, a part weighing 5.9167 grams was separated by means of dilute hydro-

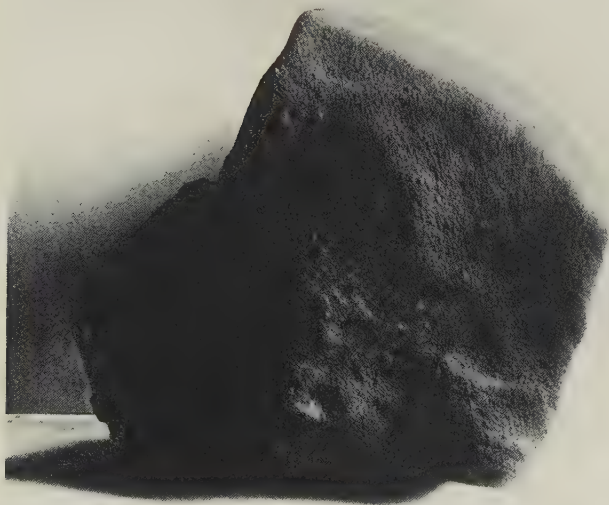


FIG. 2. Meteoric stone of Lake Brown, Western Australia, showing radiating flow-lines. $\times \frac{1}{4}$.

chloric acid into 2.9192 grams insoluble and 2.9975 soluble. Analyses were made of the attracted (partial analysis), the unattracted, and the insoluble of the unattracted, with the results shown in Table I.

These results show that the Lake Brown meteoric stone conforms to theory in having a rather low content of nickel-iron rich in nickel and ferromagnesian silicates correspondingly rich in ferrous oxide. In chemical composition it is remarkably similar to the Warbreccan (Queensland) stone,¹ the bulk analysis of which is given in the last

¹ G. T. Prior, The meteoric stones of Launton, Warbreccan . . . Min. Mag., 1916, vol. 18, p. 8.

TABLE I.

	Attracted.	Total unattracted.	Insoluble of unattracted.	Bulk analysis.	War- breccan.
{ Fe	63.79 ¹	—	—	6.10	6.03
{ Ni	11.27	—	—	1.08	1.06
{ Co	0.60 ²	—	—	0.06	0.08
{ Fe	—	4.29	—	3.98	4.09
{ S	—	2.46	—	2.28	2.31
SiO ₂	3.17 ³	42.51	52.52	39.43	39.86
TiO ₂	—	0.38	—	0.35	0.21
Al ₂ O ₃	—	2.16	5.43	2.00	1.71
Cr ₂ O ₃	—	0.19	0.40 ⁴	0.18	0.41
Fe ₂ O ₃	—	3.94	—	3.65	2.15
FeO	—	12.93	16.24	11.99	12.84
MnO	—	0.27	—	0.25	0.39
NiO	—	0.35	—	0.32	0.12
CaO	—	2.03	5.10	1.88	2.01
MgO	—	27.11	18.58	25.15	24.75
Na ₂ O	—	0.87 ⁵	1.93	0.81	0.92
K ₂ O	—	0.11 ⁵	0.25	0.10	0.06
H ₂ O(−110°) ...	—	0.08	—	0.08	} 0.80
H ₂ O(+110°) ...	—	0.54	—	0.50	
P ₂ O ₅	—	0.33	—	0.31	0.26
Insoluble ...	10.73	—	—	—	—
	—	100.55	100.45	100.50	100.06

¹ i. e. 66.04 total iron estimated less 2.19 contained in the soluble portion of admixed unattracted.

² Probably too low, owing to possible loss on ignition of the α -nitroso- β -naphthol precipitate.

³ From soluble silicate; the other constituents of which were not determined here.

⁴ From analysis of unattracted.

⁵ From analysis of insoluble.

column above. The approximate mineral composition of the stone is: nickel-iron 7, troilite 6, olivine 36, pyroxene 38, feldspathic material 8, ferric oxide, water, &c., 5%. The ratio Fe:Ni in the nickel-iron is about $5\frac{1}{2}$, and in conformity with this the ratio MgO:FeO in the ferromagnesian silicates is about $3\frac{1}{2}$. The composition of the stone may therefore be expressed by the symbol $f_7 n_{5\frac{1}{2}} m_{3\frac{1}{2}} t_6$, where f denotes the percentage of nickel-iron, n the ratio of iron to nickel in it, m the ratio of MgO to FeO in the ferromagnesian silicates, and t the percentage of troilite.

The Lake Brown meteoric stone is an intermediate hypersthene-chondrite of Baroti type.

*On the occurrence of native gold at Hope's Nose,
Torquay, Devonshire.*

(With Plate VI.)

By ARTHUR RUSSELL.

[Read January 15, 1929.]

SOME thirty-five years or so ago small quantities of free gold were found in calcite in or near a crush-breccia filling an east and west fault, in the patch of Middle Devonian limestone which forms that portion of the coast known as Daddy Hole Plain directly south-east of Torquay. The name of the actual discoverer I have been unable to ascertain, neither do any specimens appear to have been preserved; but the late Mr. T. Harrison, the then proprietor of the Queen's Hotel, Torquay, and several other persons subscribed about £100, and a small amount of prospecting work was carried out, apparently with little result. The only reference to this discovery which I know of is a brief one in 'The geology of the country around Torquay' (Mem. Geol. Survey, 1903, p. 48).¹ To Mr. B. W. Stedham of Torquay I am indebted for the additional particulars given and also for pointing out to me the exact spot, which is on the side of a fissure formed by a large pinnacle of rock standing away from the cliff below the old quarry.

The occurrence which forms the subject of the present note was discovered in a curious way. In April, 1922, Professor W. T. Gordon of King's College, London, with a party of students, was pointing out the geological features of Hope's Nose, a headland two miles east of Torquay, and in examining a small calcite vein, of which many traverse the Middle Devonian limestone on the foreshore at this spot, the chance blow of a hammer revealed the calcite to be tenaceous owing to the presence of many sprigs of gold. A brief record of this find was published by Professor Gordon in 'Nature' (London, 1922, vol. 109, p. 583, 1 fig.). Stress of other work prevented him,

¹ This record has been repeated in at least one local guide-book and in W. G. Shannon's Short guide to the geology of Torquay, 1925, p. 7.

however, from more carefully examining the spot. In 1927, with Professor Gordon's concurrence and in company with my brother Sir Charles Russell and Captain G. M. Puckle, a careful examination of Hope's Nose was made, and specimens of arborescent gold were obtained from five distinct calcite veins within the space of about forty yards. In 1928, permission having been most courteously given by Major H. A. Garrett, the Borough Engineer of Torquay, a couple of shot holes were put in on the most promising looking of the veins, and a number of very remarkable specimens of arborescent gold were obtained. The exact spot at which the gold occurs is on the flat rocky shore just above high-water mark, east of and adjoining the old limestone quarry, and at a point where the first small indent above the Torquay sewage outfall is marked on the six-inch Ordnance Map (Devonshire, Sheets 116 S.E. and 122 N.E., 1906).

The geological structure of Hope's Nose has been often described, and it is sufficient to say that its eastern seaboard is formed of thick-bedded pale grey to pinkish compact Middle Devonian limestone containing corals. About the sewage outfall and south of it the limestone becomes thin bedded and slaty. On the flat rocky shore the thick-bedded limestone is traversed by a number of calcite veins and strings, which from the presence of slickensided faces appear to be of the nature of minor fault fissures. They have a direction about 20° north of west (magnetic) and vary in width from less than an inch to a foot or more, the width of the veins increasing as they run seawards, where for the most part the sea has completely eroded the vein-filling, leaving open sea-swept chasms. The strike of these veins can be traced for roughly only about 30 yards, from low-water mark to the low cliff dividing the foreshore from the quarry, at which latter point they are cut off by a fault. Of these veins, five have yielded specimens of free gold, in each case within a few yards of the base of the low cliff where the vein-filling has not been removed by the agency of the sea. Many very similar calcite veins are to be seen in the adjacent quarry, but although careful search was made, no trace of gold has been seen. Very close scrutiny is necessary to detect the gold, which stands out from the eroded calcite on the outcrops, since it is often masked by a coating of lichen or sea-slime, while some of the richest specimens were obtained from remnants of the vein-filling adhering to the limestone walls, the whole central portion having been eroded away by the sea.

The calcite which fills the veins has a mottled appearance and is of

two varieties, coarse cleavage pinkish-brown, and fine-grained cream-buff, the gold being invariably confined to the latter. The predominating pinkish-brown calcite was apparently the first to crystallize out and it forms the outer portions of the veins. Where cavities exist it assumes drusy-surfaced scalenohedra surmounted by curved-faced primary rhombohedra. The colour is due to included red haematite. The fine-grained cream-buff calcite usually occupies the central part of the veins and also fills the interstices between the coarse pinkish-brown crystals; it is developed, however, much more sparingly and is rarely continuous for any distance. Here and there are small cavities filled with yellowish or brownish highly ferruginous dolomite, which forms small distinct rhombohedra, or has altered to a friable ochre which in one case carries minute crystals of gold. Aragonite also occurs in some parts of the veins, forming snow-white silky radiating masses; and as *flos-ferri*, one cavity having yielded small worm-like stalactites of grotesque form. Some of the veins, particularly where narrow, are partially filled with calcite very heavily charged with minute scales of haematite forming a dense dull-red iron-ore, and one specimen of this shows dendritic crystallized gold. The only other mineral observed in these veins is muscovite, which occurs as minute scaly rosettes.

The gold is nearly always present as delicate dendritic or arborescent forms, which are extremely beautiful when partly freed from the enclosing calcite by immersion in dilute hydrochloric acid (Plate VI, fig. 1). Many of these growths are sometimes contained in quite a small piece of the vein-stuff, and in one or two cases attain a length of 5 cm. In general they consist of fern-like structures formed of a central rod with graduated branches and sub-branches all at 60° ; each branch and sub-branch being usually terminated by a more or less distinct crystal (fig. 2). Twinning on the octahedron (111) is responsible for this arrangement. Examination under the microscope shows the individual crystals to be much elongated and misshapen, and in most cases they fail to give even moderately good measurements on the goniometer. The following forms have, however, been noted with certainty: (100), (111), (110), (210), and perhaps (311). On two of the specimens of the silver-white gold are some minute simple cubes grouped in parallel position, one of these crystals showing a single face (110).

In colour the gold varies from a bright rich gold to dull yellow; while in one vein it is almost silver-white, in this case being thickly distributed in dendritic form through a nearly white calcite.

The following assays, which were most carefully made for me by Mr. A. W. Dannatt of the Royal School of Mines, are interesting in that they show the gold to be of very exceptional fineness, and that even the silver-white gold (nos. 2 and 3), which from its appearance led one to suspect a high silver content, contains only a comparatively small amount of silver, far below that variety to which the term electrum has been applied. Metals of the platinum group are absent.

		No. 1, Bright rich gold.	No. 2, Silver-white gold.	No. 3, Silver-white gold.
Au	...	98.11	91.59	92.53
Ag	...	1.89	8.41	7.47

Altogether the occurrence is an interesting one, as, apart from the exceptional beauty of the arborescent forms in which the gold occurs, the fact of it being present in calcite veins in Middle Devonian limestone is I believe unique. Conjectures as to the origin of the gold would be futile. The finding of a mineral such as gold in so unexpected a quarter is moreover an object-lesson to the mineralogist in the field and impels one to look for similar occurrences in other of the Middle Devonian limestone tracts of the west of England.

EXPLANATION OF PLATE VI.

Native gold from Hope's Nose, Torquay, Devonshire.

FIG. 1. Fern-like growths partly freed from the enclosing calcite by the action of dilute acid. $\times 1\frac{1}{4}$. (For this photograph I am indebted to Mr. Gilbert Adams, who took considerable pains with this difficult subject.)

FIG. 2. Isolated sprays. $\times 20$. In the larger spray, the terminal crystals are rhombic-dodecahedra. In the smaller spray, the branches consist of elongated spike-like cubes. (For this photomicrograph I am indebted to Mr. A. F. Hallimond.)

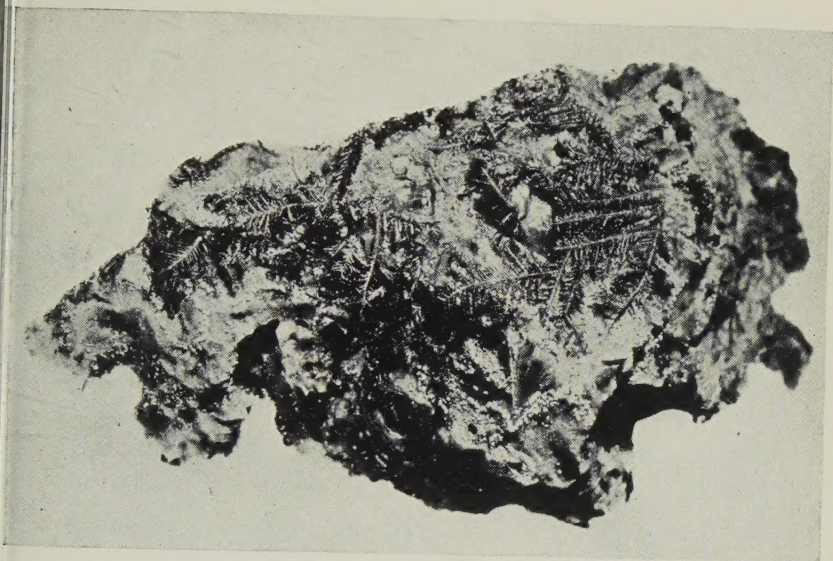


FIG. 1.

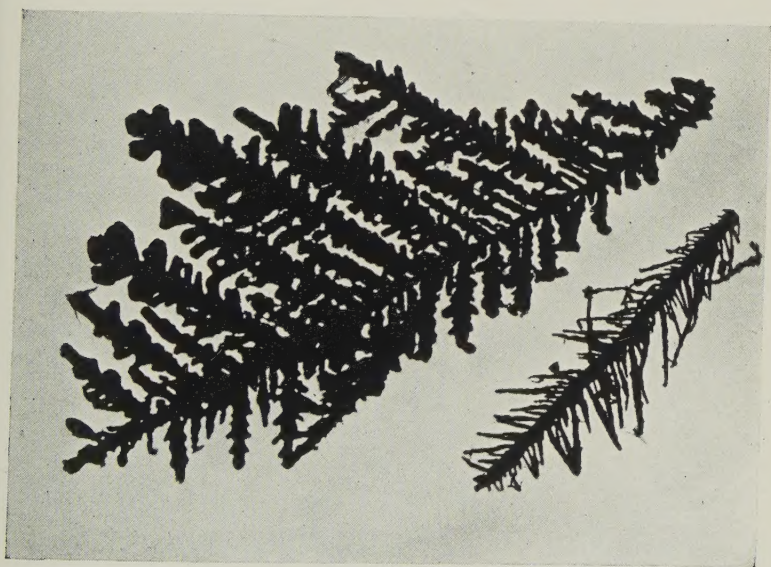


FIG. 2.

ARTHUR RUSSELL: NATIVE GOLD FROM TORQUAY, DEVONSHIRE.

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MINERALOGICAL MAGAZINE

CONTENTS OF NO. 126

(September, 1929)

PAGE

L. A. N. IYER: A study of the calc-gneisses, scapolite-gneisses, and cordierite-garnet-sillimanite-rocks of Coimbatore, Madras Presidency; with comparison to other similar occurrences in India. (With Plate V)	121
F. A. BANNISTER: A relation between the density and refractive index of silicate glasses, with application to the determination of imitation gem-stones	136
G. T. PRIOR: The meteoric stone of Lake Brown, Western Australia	155
A. RUSSELL: On the occurrence of native gold at Hope's Nose, Torquay, Devonshire. (With Plate VI)	159

MINERALOGICAL ABSTRACTS

(Vol. 4, No. 3, Pages 97-144)

X-rays and Crystal-structure (p. 97).—Radioactivity (p. 112).—Meteorites and Tektites (p. 117).—Rock-forming Minerals and Petrology (p. 123).—Miscellaneous (p. 135).

PAGE	PAGE	PAGE	PAGE
ADAMSON, J. 106	ELLSWORTH, H. V. 113	LONSDALE, K. 112	SCHIEBOLD, E. 111
ALLARD, G. 98	ERDMANNSDÖRFFER, O. H. 127	LUNN, J. W. 134	SCHILLING, A. 114
AMINOFF, G. 103	FEIGL, F. 141	MACCARTHY, G. R. 144	SCHNEIDER, W. 98
ANDREATTA, C. 136	FENNER, C. N. 114	MACHATSCHKI, F. 102	SCHURINK, H. B. J. 112
ASTBURY, W. T. 97	FLEET, W. F. 133	MACKIE, W. 134	SCHWARTZ, G. M. 144
BARTH, T. 127	FOYE, W. G. 144	MARK, H. 98	SHAND, S. J. 124
BERRY, J. A. 130	FRIAUF, J. B. 100	MAURSTAD, A. 107	SHANNON, E. V. 118, 142
BIANCHI, A. 135-6	GANTER, F. 98	MAZZA, L. 99	SKERL, J. G. A. 133
BÜHM, J. 98	GEORGE, W. H. 97	MEHL, R. F. 100	SMITH, S. W. J. 121
BOWEN, N. L. 123	GILLSON, J. L. 129	MELLE, F. A. VAN 112	SMITHSON, E. 133
BOYER, T. 107	GOLDSCHMIDT, V. M. 103	MENZER, G. 111	SMYTH, C. H. 128
BRADLEY, A. J. 99, 100	GOSSNER, B. 107-11	MERRILL, G. P. 121	STURDIVANT, J. H. 105
BRAGG, W. L. 97	GOTTFRIED, C. 108	MERWIN, H. E. 104	TARR, W. A. 143
BRENTANO, J. 106	GREGORY, C. H. 100	MILLOSEVICH, F. 117	TAYLOR, W. 107
BRÜCKL, K. 107-11	GREIG, J. W. 126	MÜGGE, O. 140	THOMSON, E. 142
BURRI, C. 125	HARRIS, J. W. 134	MUSCHNUG, F. 107-11	TOPPING, J. 105
CAGLIOTI, V. 138	HARTMANN, H. 99	NAGY, L. J. 106	TSCHERKAS, W. 123
CARDOSO, G. M. 111	HENDRICKS, S. B. 103-4	NASINI, A. G. 99	TSCHIRWINSKY, P. 119, 123
CAROBBI, G. 138-9	HENGSTENBERG, J. 98	NININGER, H. H. 118	TURNER, H. W. 116
CARFANESE, T. 137	HOFER, A. 117	OFTEDAL, I. 101	VEGARD, L. 107
CAVINATO, A. 137	HOLMES, A. 113	OGG, A. 107	WAHL, W. 123
CHEKKAS, V. 123	KERR-LAWSON, D. E. 115	OSANN, A. 129	WASHINGTON, H. S. 131-3
CHIRVINSKY, P. N. 119, 123	KEYES, M. G. 131	PALACHE, C. 118	WEGSCHEIDER, R. 140
CHUDOBA, K. 140	KIRSCH, G. 112	PANETH, F. 122	WESTGREN, A. F. 99
COTTON, L. A. 113	LACROIX, A. 117, 122	PAPISH, J. 141	WHEERRY, E. T. 98
COULSON, A. L. 118	LÁNTI, B. 97	PARDEE, J. T. 129	WILSON, B. H. 117
CROOK, A. R. 144	LARSEN, E. S. 127, 129	PARSONS, A. L. 103	WINCHELL, A. N. 143
DAY, T. C. 135	LEE, O. L. 141	PASTORE, F. 120	YARDLEY, K. 112
DEE, A. A. 121	LEITMEIER, H. 141	PAULING, L. 105	YOUNG, J. 121
DICK, A. B. 134	LEONARD, R. J. 144	PEMISTER, T. C. 130	ZACHARIASEN, W. H. 102-5
DICKINSON, R. G. 103	LEONHARDT, J. 122	PIGGOT, C. S. 113-14	ZAMBONINI, F. 138
DOUGAL, J. W. 133	LONSDALE, J. T. 128, 143	POOLE, J. H. J. 116	
DOUGMAN, J. 127		POSNJAK, E. 106	
DUCLOUX, E. H. 119-21		ROSS, C. S. 128	
EBERT, F. 99		RUTHERFORD, R. L. 144	
		SCHALLER, W. T. 143	

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